BBN TECHNOLOGIES

High-Throughput Distributed Spacecraft Network Architecture and Multiple-Access Technologies (HiDSN)

SpaceVPN

Earth Science Technology Conference 2004

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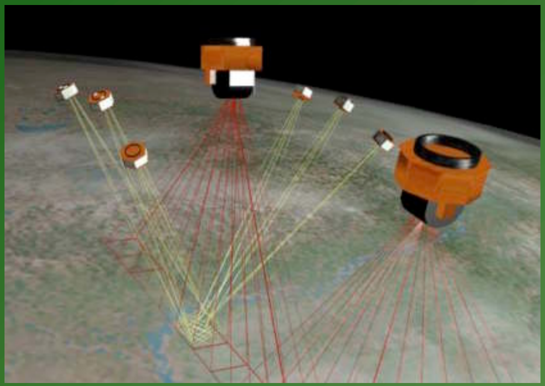
Dr. Marcos A. Bergamo, Principal Investigator

mbergamo@bbn.com

Key networking challenges of planned/future collaborative multi-spacecraft missions

Leonardo



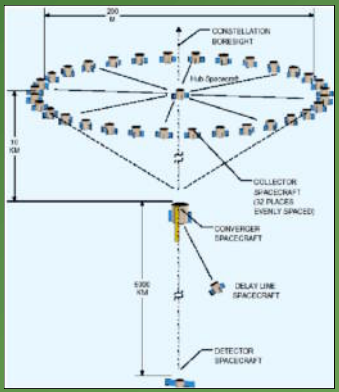
Loose Formations:

6 -12 nodes, 0.3 - 3.0 Gbps

d: 100 - 2000 Km, Δd: < 50 m

Terrestrial Planet Finder (TPF)

Micro-Arcsecond X-ray imaging Mission (MAXIM)

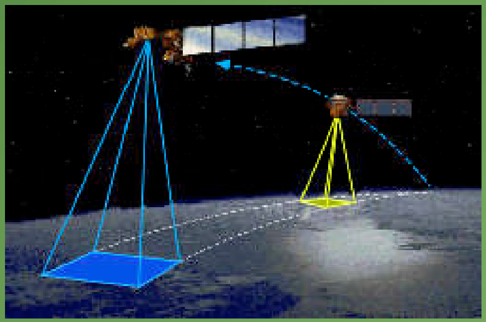


Tight formations:

5-36 nodes <1Mbps

d: 100 - 1000 m Δd: ~mm to nm

Landsat & Terra



Sensor Web collaborative missions:

Increasing 20 kbps - 100 Mbps

d: 100 - 2000 Km Δd: <km

Geospace Electrodynamic Connections, (GEC)

Clusters:

5 nodes < 1 Mbps

d: 10 - 20,000 Km Δd: 100 m

Design Challenges

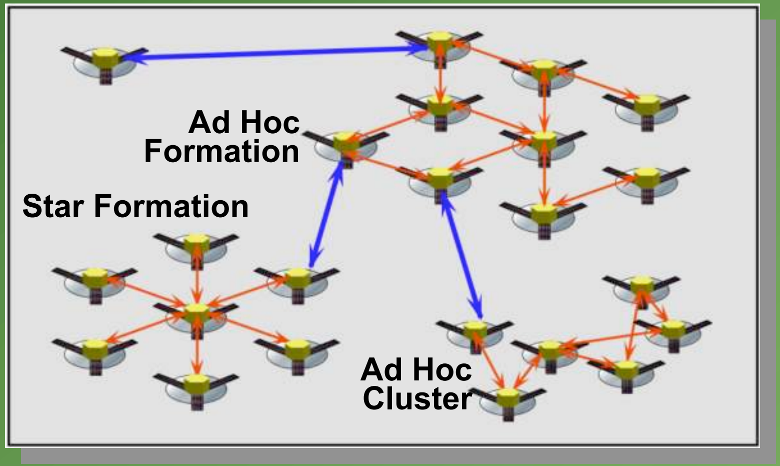
- Widely varying requirements
- Agile inter-spacecraft communication
- Position measurement (range, velocity, angular)
- High-capability/modularity/reconfigurability
- Wide-ranges (distances, velocities, data rates)
- Varying traffic mix (stream/bursty)
- Varying application QoS (BER, delay, synchronization)

High-Throughput Distributed Spacecraft Network

Project Goals and Objectives

Goals

Develop the technologies necessary to enable intercommunications between future NASA spacecraft flying in formation, in clusters, or in constellations.



Objectives

- Define flexible network architecture that that can be used as a baseline for future NASA spacecraft flying in formation, in clusters, or in constellations.
- Develop efficient transmission and multiplexing technology for agile, variable/high data rate inter-spacecraft communications.
- Develop the MAC and sub-network protocols that can enable a flexible means of internetworking and to efficiently move data over varying space distances.

High-Throughput Distributed Spacecraft Network

Relevance and Innovations

Enterprise Relevance

Creates a vertically integrated network infrastructure for establishing and maintaining a high-throughput communications network among constellations of spacecraft operating in diverse orbits for data transfer from satellite-to-satellite, satellite-to-aircraft and satellite-to-ground configurations

Impact/Innovation

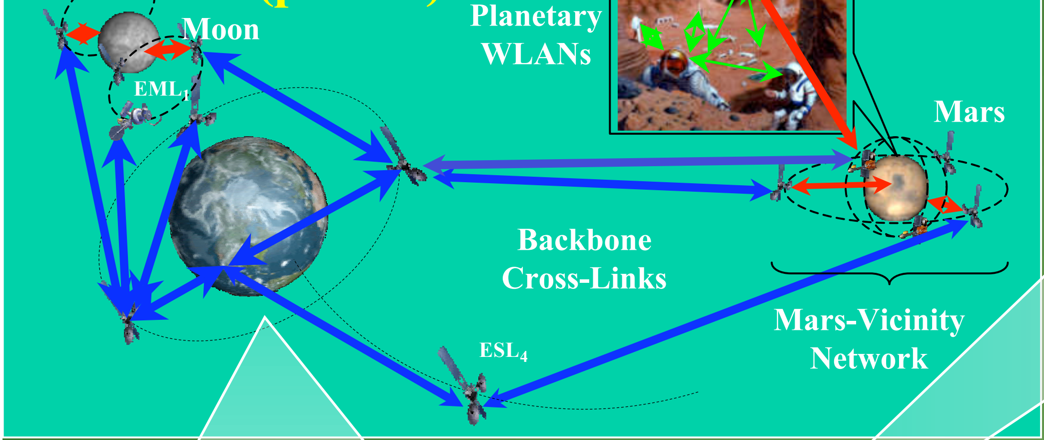
- Self-forming techniques for networks in space
- Topology independence (formation flying, multiple orbits, etc.)
- Integration of *satellite/satellite/aircraft/ground* communications
- Wide range data rates (e.g. 100Kbit/s — 800 Mbit/s) for maximum connectivity over varying space distances
- Interference-free links and throughput maximization with integrated spatial/time/code multiplexing

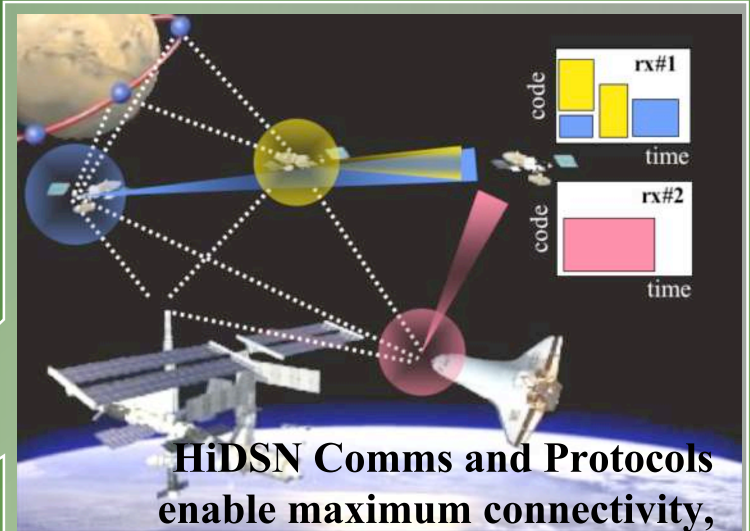
Utilizes BBN's TCeMA,

A novel data-link protocol devised from the combination of Time Division Multiple Access (TDMA) with Code Division Multiple Access (CDMA) to obtain TDMA with CDMA encoding Multiple Access (TCeMA).

HiDSN: Technology Base for Internet-Based Networking in Space

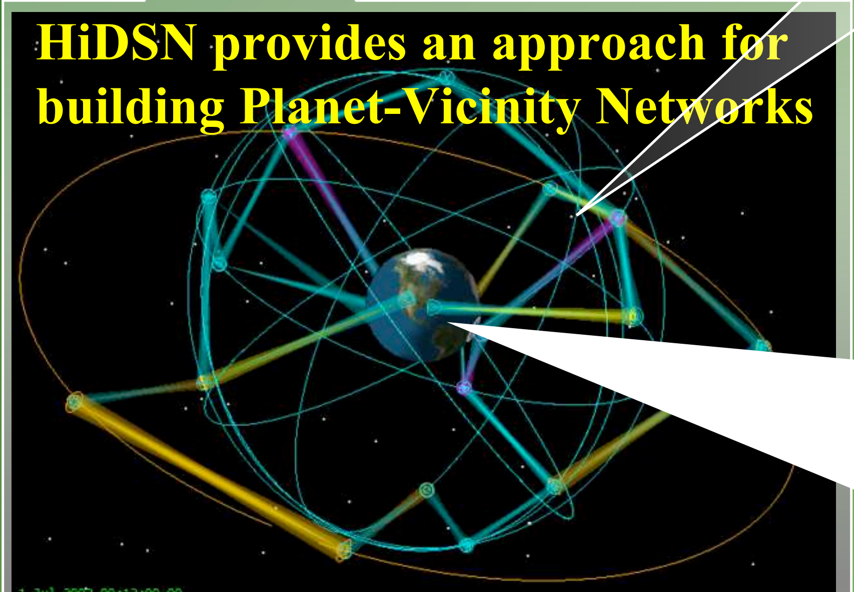
NASA's Backbone Vision (partial)

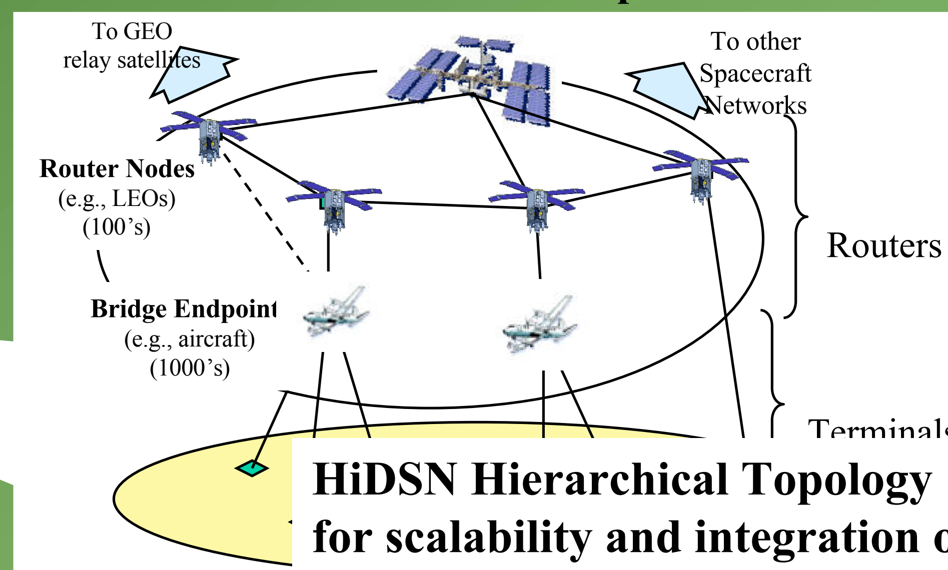




HiDSN Comms and Protocols enable maximum connectivity, minimum interference at space distances

HiDSN provides an approach for building Planet-Vicinity Networks



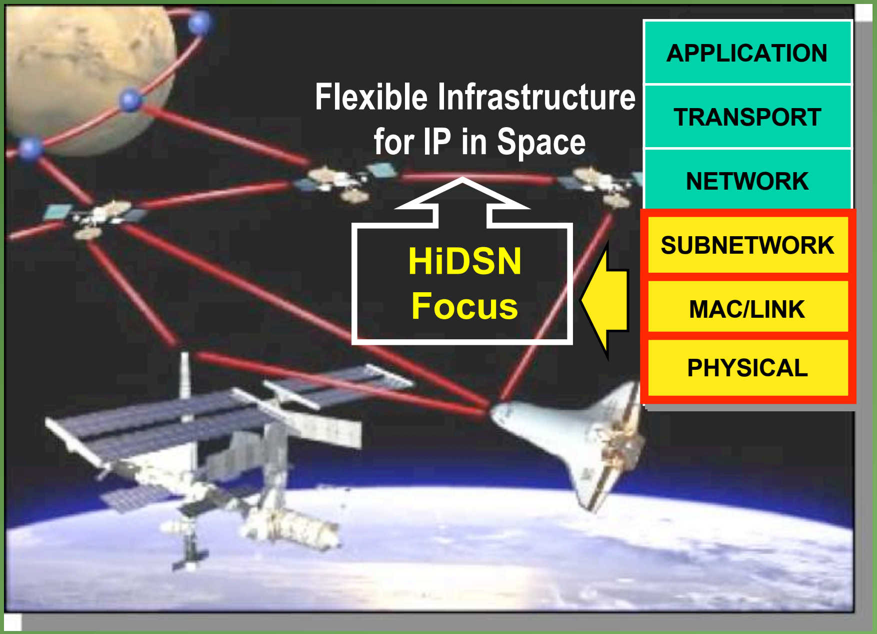


HiDSN Hierarchical Topology for scalability and integration of sensors, rovers and aircrafts

High Throughput Distributed Spacecraft Network (HiDSN)

What has been developed

1. *SYSTEM DESIGN* — Leverages terrestrial ad hoc technologies and addresses the uniqueness of spacecraft networking
2. *LABORATORY TESTBED* — Demonstrates the technical feasibility of key PHY-/MAC-Layer technologies
3. *OPNET SIMULATION* — Demonstrates protocol scalability and performance for a range of scenarios



How is intended to be used

Network Design: Flexible architecture and protocols that can be tailored to specific missions

Transmission/Encoding Technologies: Can be incorporated in any system with demanding multiplexing/power-efficiency requirements

Potential Use by NASA

VPN-Secure Experimenter access to on-board sensor data and instruments: ESTO's SpaceVPN (Contract # NNC04CB16C)

Planet-Vicinity Networks (Earth, Mars, etc.)

Space Internet Backbone (?)

Topics

- Network overview
  - How we find neighbor spacecraft
  - … close the link at high data rates
  - … reuse the spectrum multiple times over
  - … integrate time-code and spatial multiplexing
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- Lab Testbed and Results
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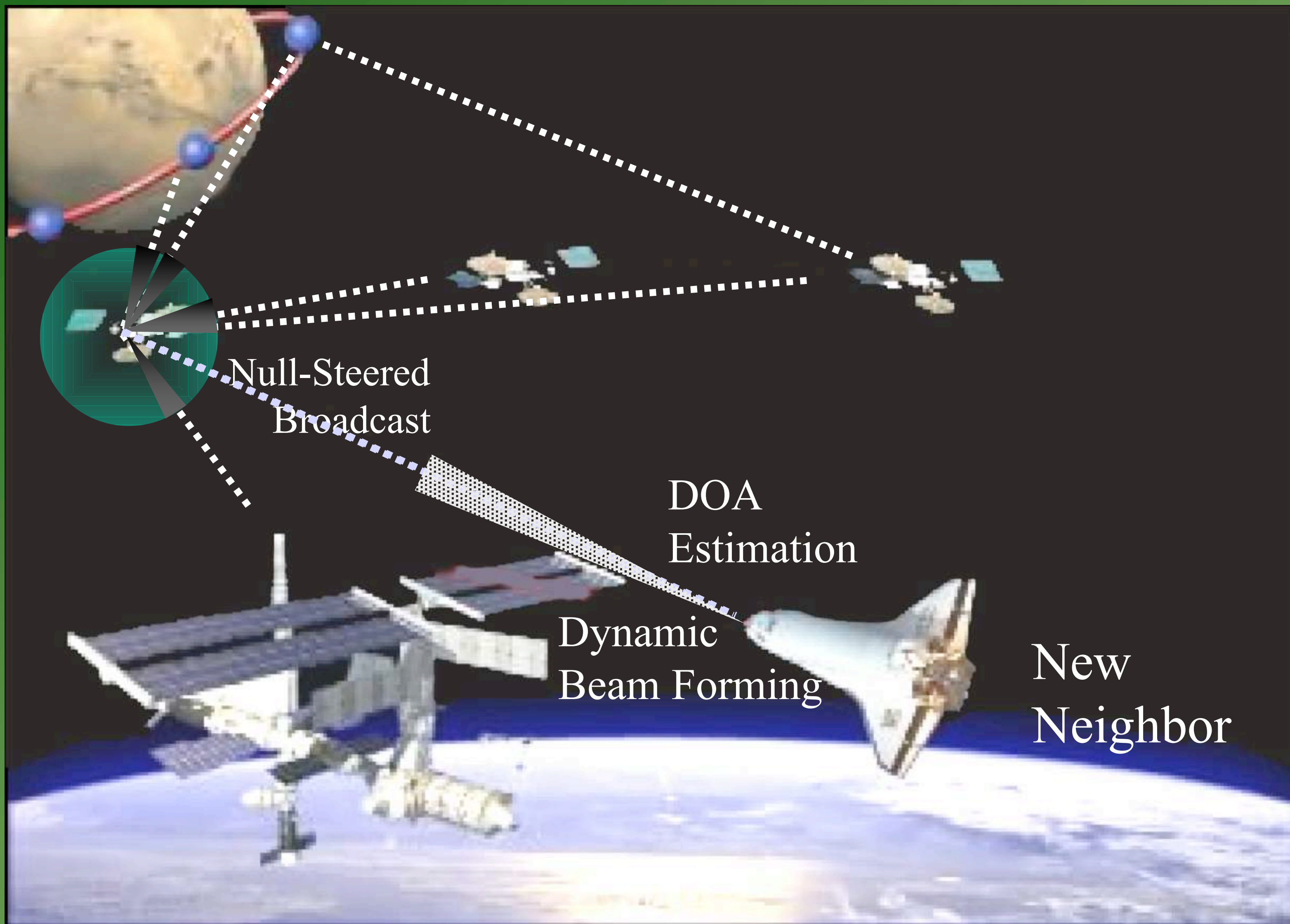
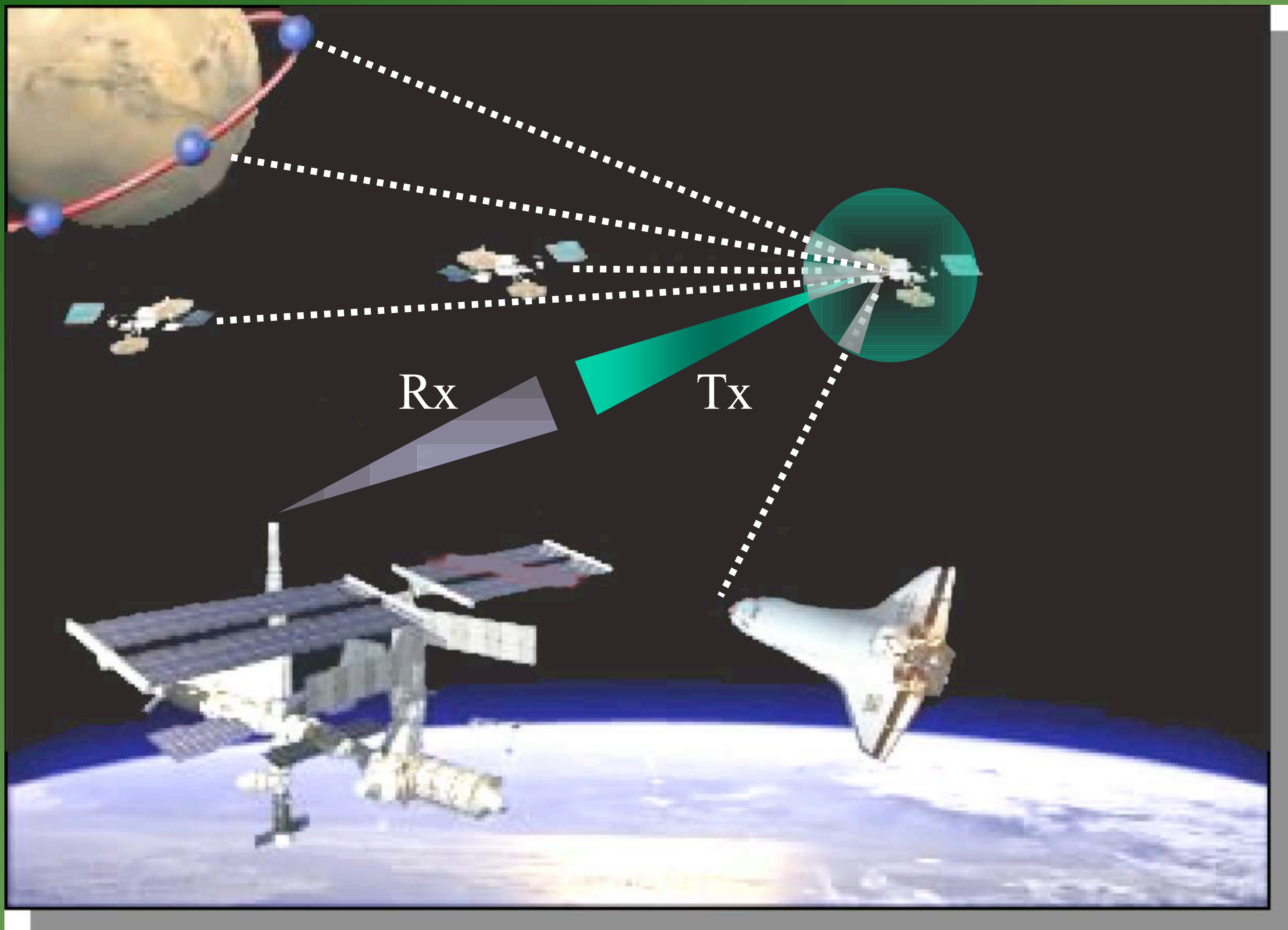
  - IPSec-secure experimenter access to on-board instruments

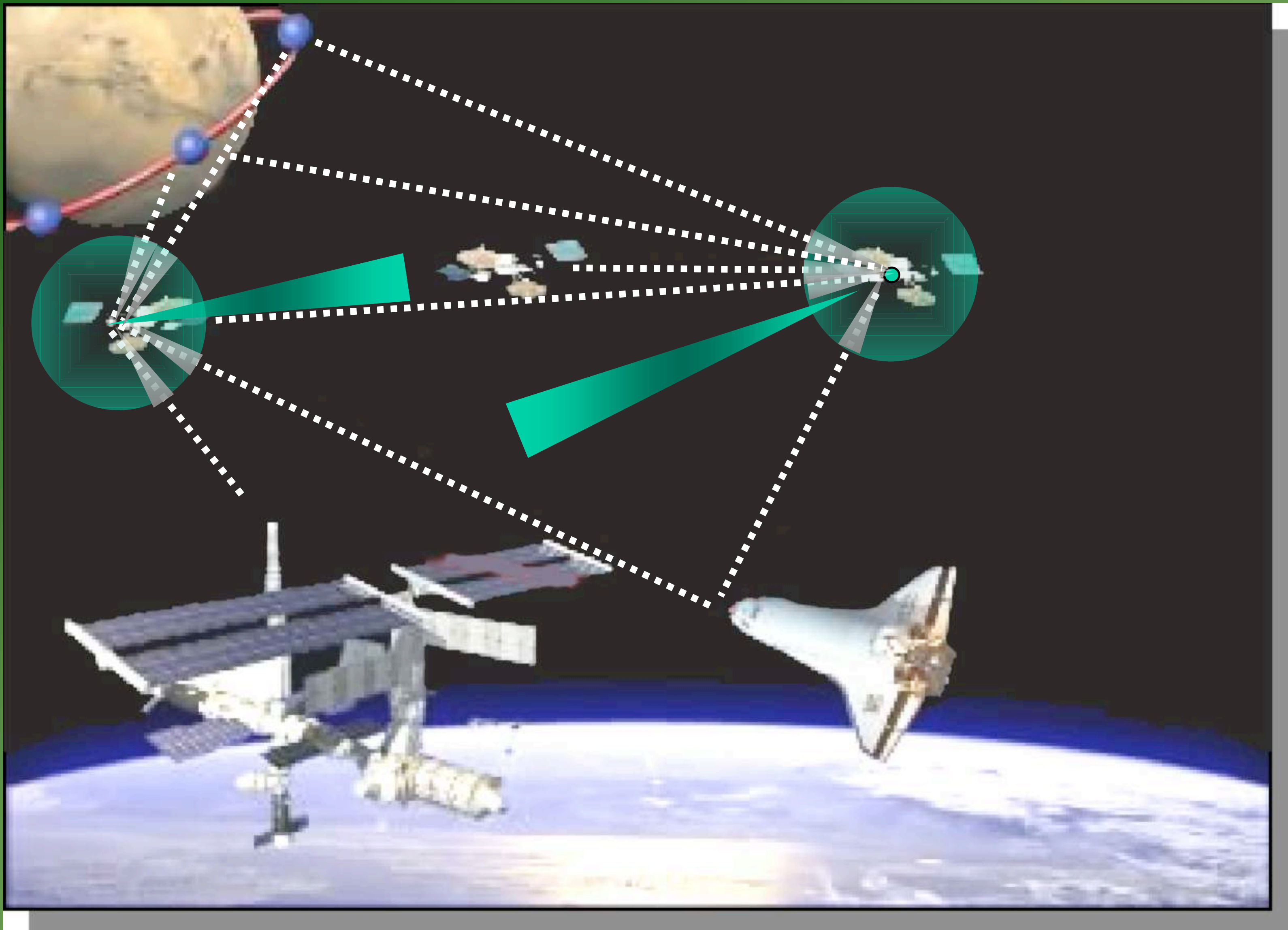
How we
1. Perform Neighbor Discovery without interference …



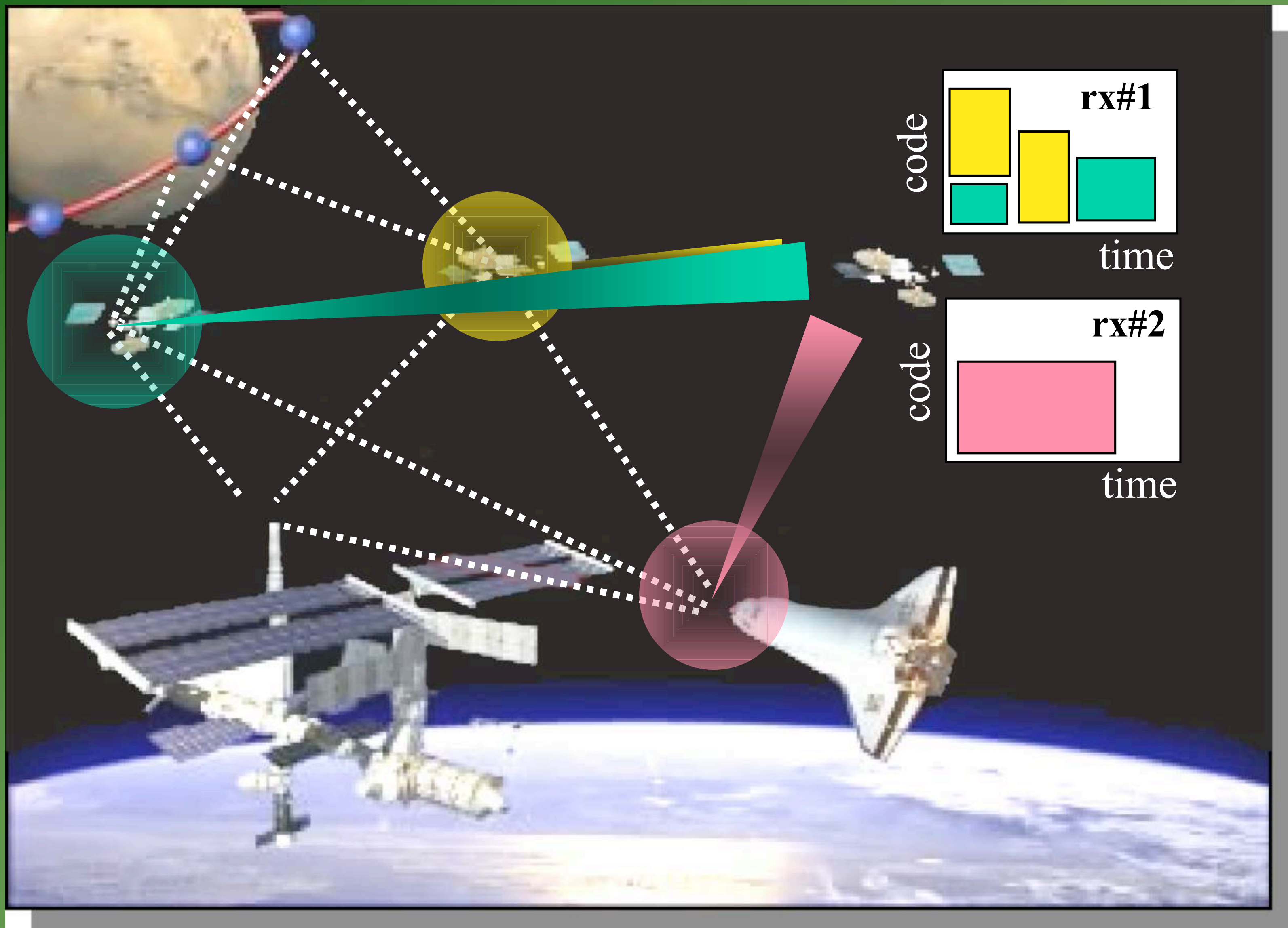
2. Transmit at a high-data-rates without causing interference to neighbor nodes...



3. Achieve multiple times over reuse of the spectrum with spatial multiplexing



4. Integrate time, code and spatial multiplexing to close the links, meet QoS requirements and maximize throughput



HiDSN Technology Summary

PHYSICAL Layer

- Transmission at Ka-Band for high data rates with small array antennas
- Null Steered Digital Beam Forming for transmissions without interference
- Variable-Rate Links (e.g., 100 Kb/s to 800 Mb/s) for maximum connectivity
- Constant Power Split-Phase Modulation for transmission power efficiency

MAC Layer

- Multiple Access integrates spatial multiplexing with TCeMA
- Frame and Bandwidth Allocation Mechanisms support for neighbor discovery, spatial & temporal synchronization, and various bandwidth allocation strategies: contention, recurring (short term) and volume-based (long-term)

SUB-NETWORK functions include:

- Neighbor Discovery Protocol
- Network Synchronization Protocol
- Decentralized Routing Protocol
- Node Affiliation Protocol
- Packet Forwarding Protocol
- (Multiple-Path Protocol)

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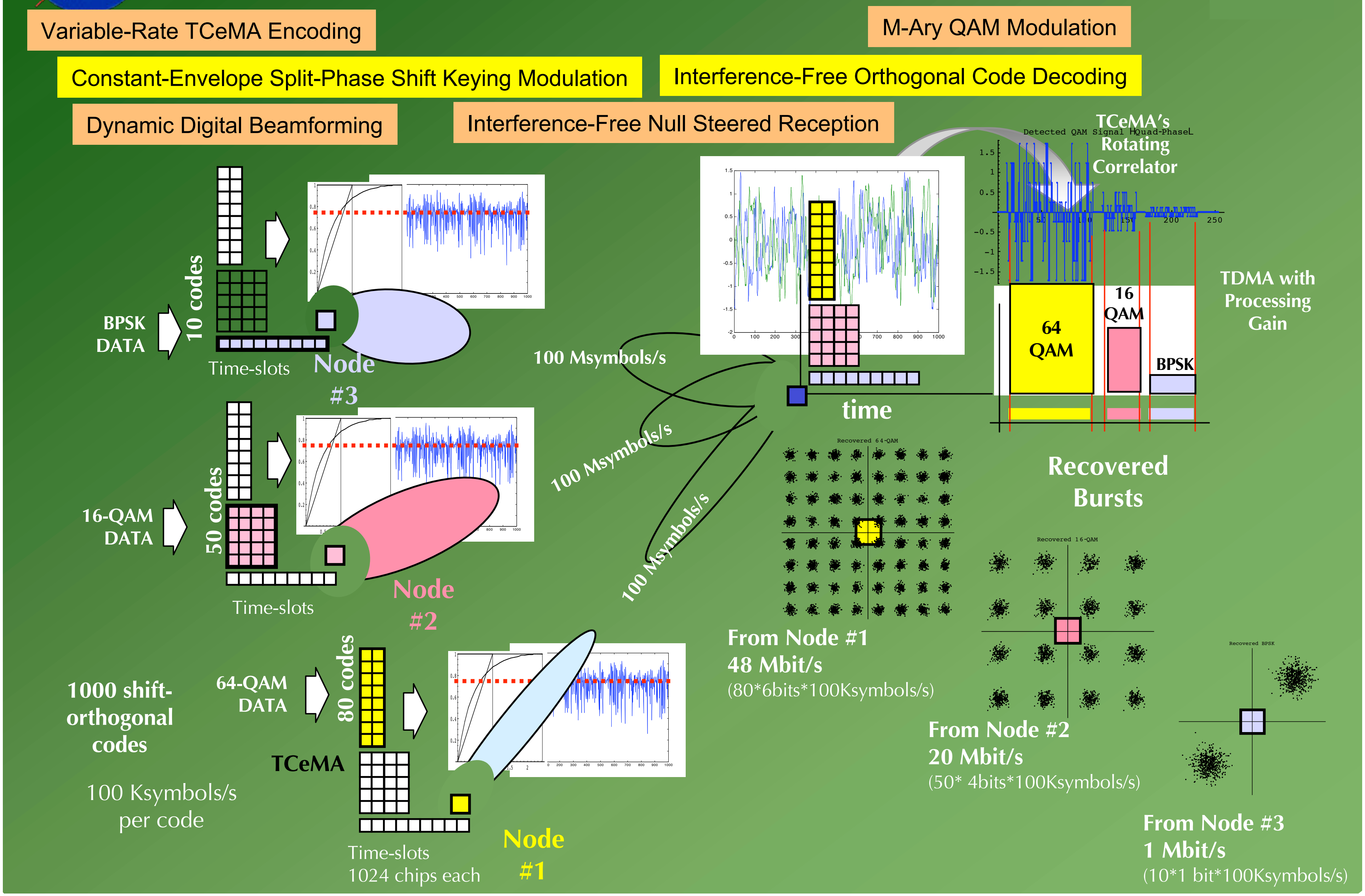
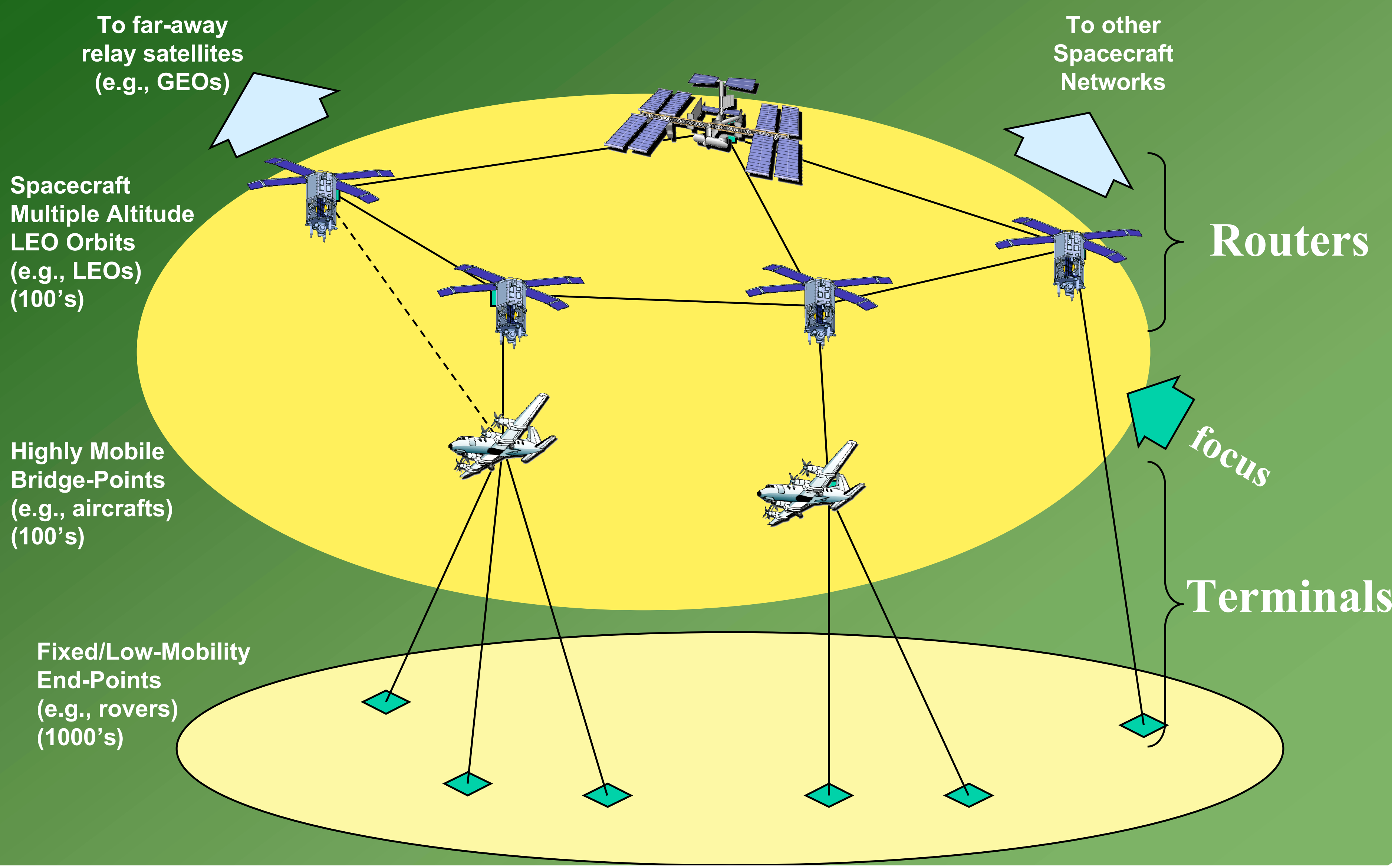
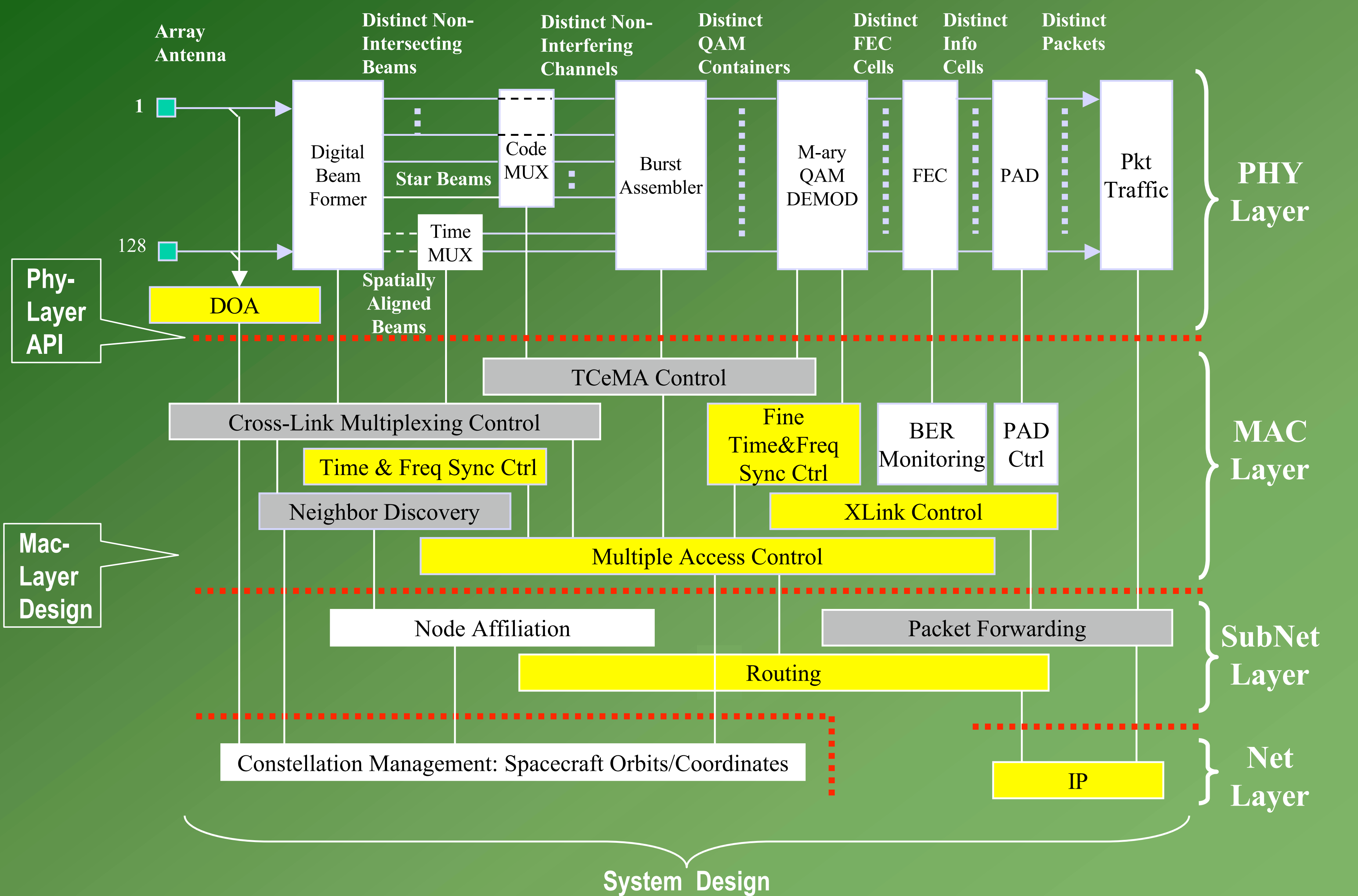
Key Physical and MAC-Layer Technologies



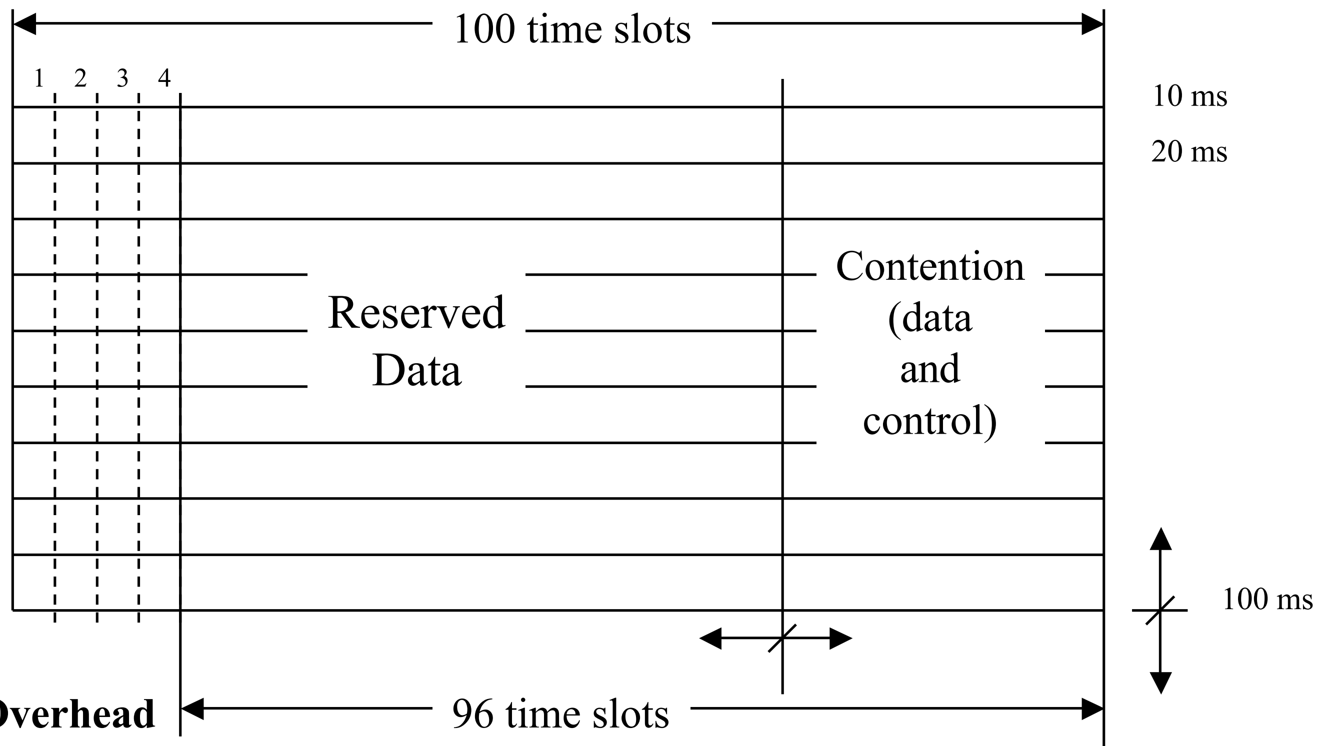
Network Elements



HiDSN System: Layers and Functions



The HiDSN Frame capacity is used mostly for data (96%) and include a small overhead area (4%) for neighbor discovery, node synchronization and burst transmission control

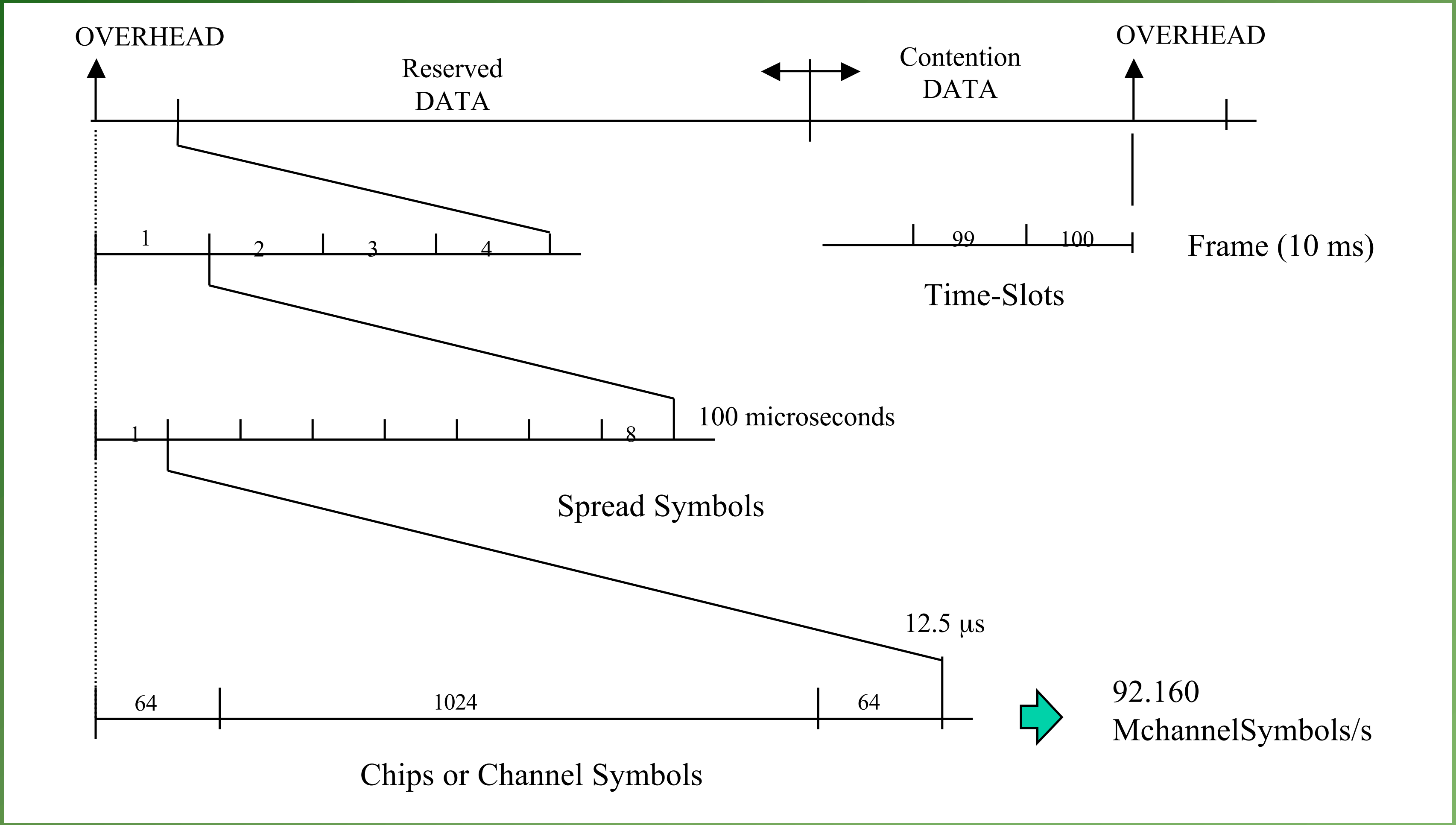


Overhead

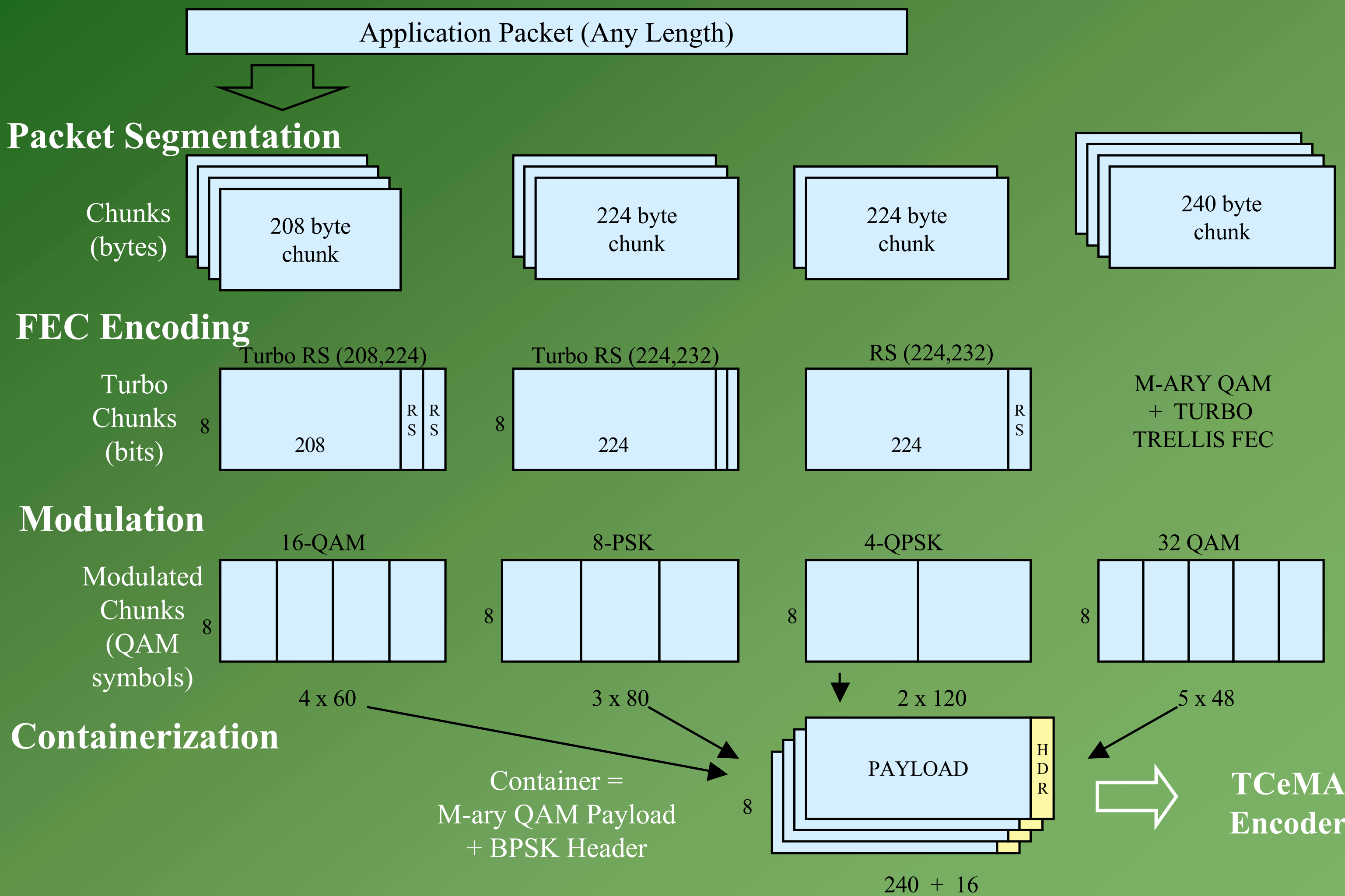
4 time slots

1. SYNChronization
2. ACTivity
3. CONTention (look ahead)
4. DISCovery

Time Slot Composition



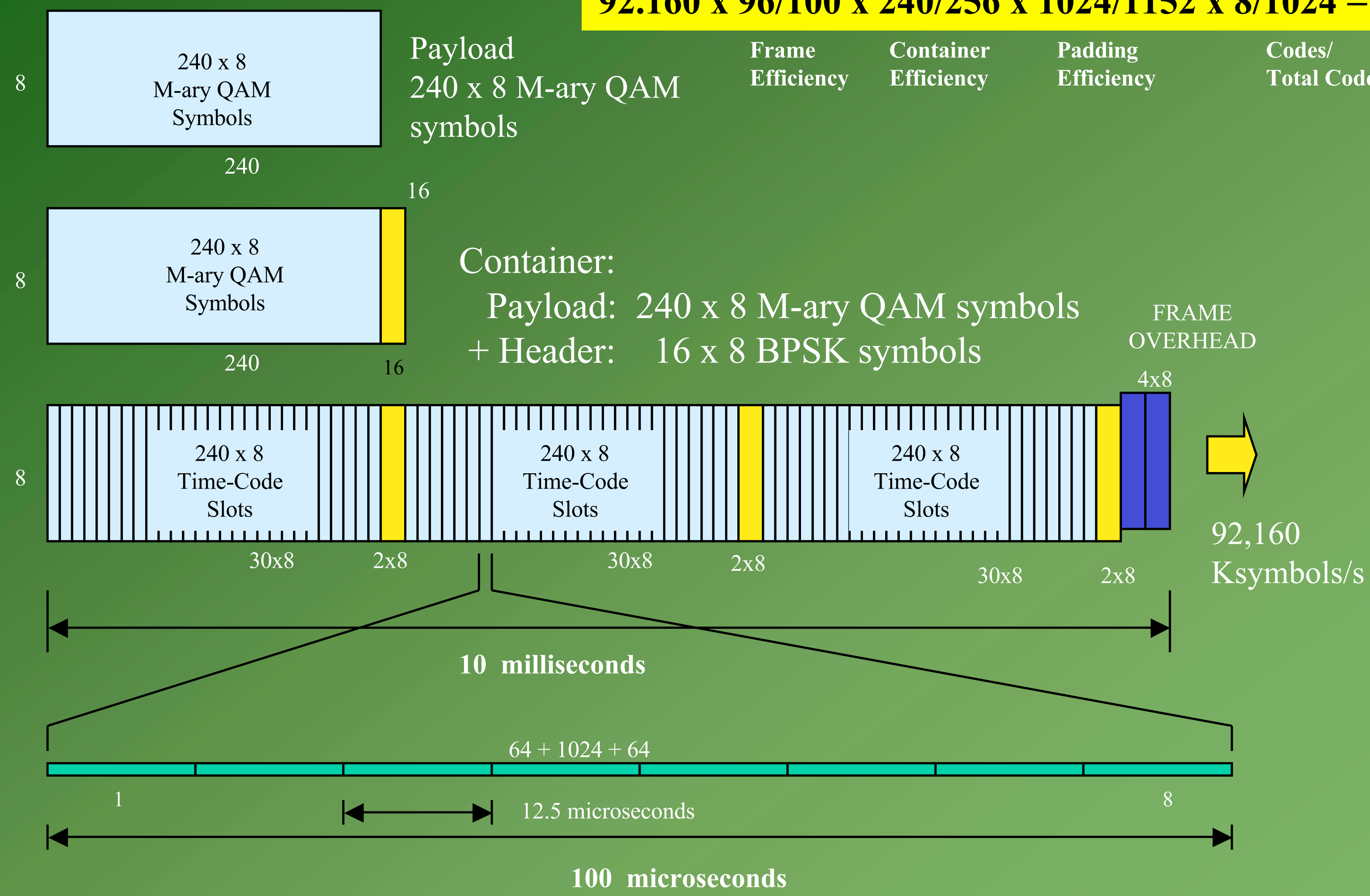
Packets segmentation, FEC-encoding, QAM-Modulation and Containerization



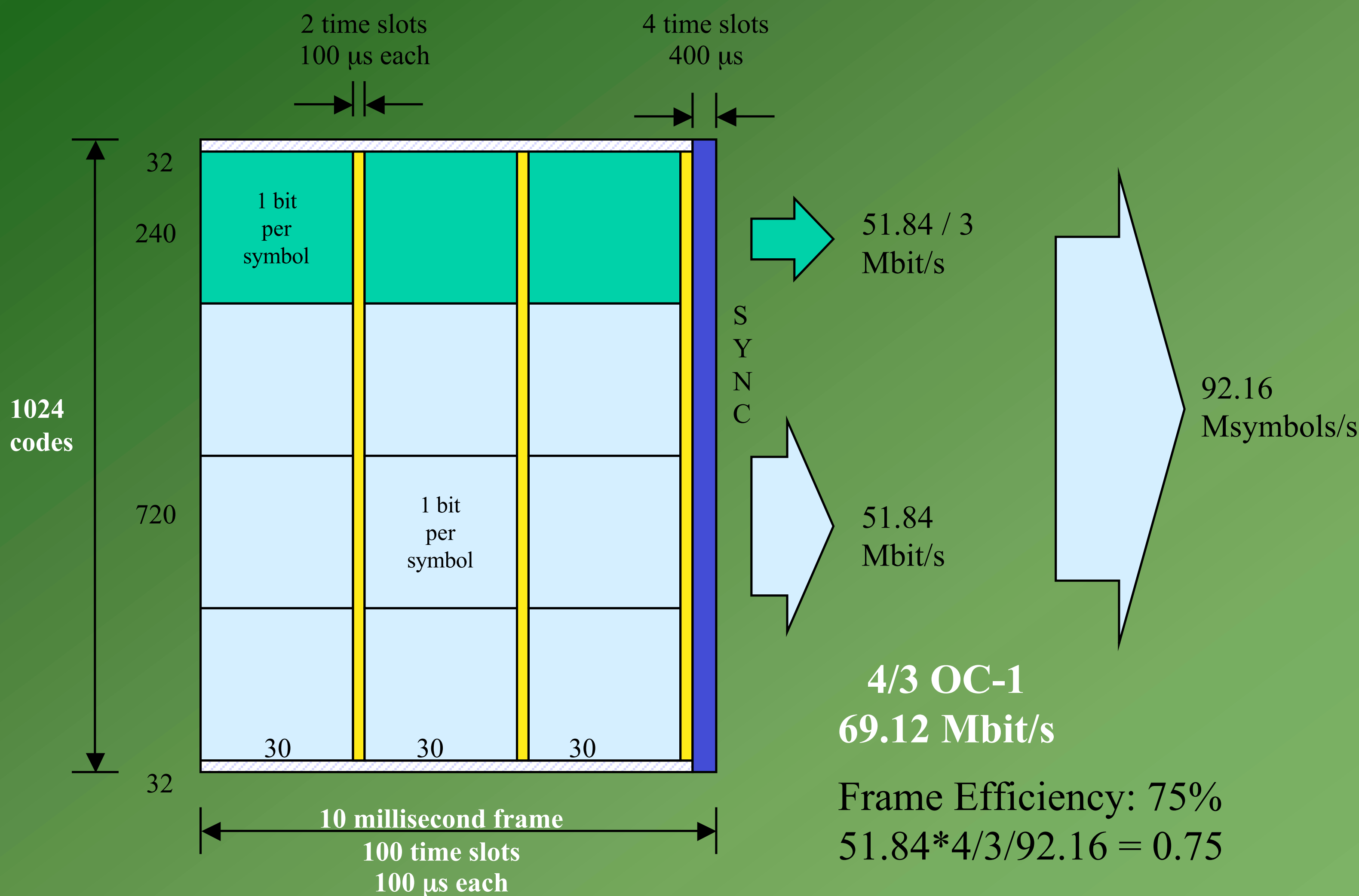
Container Structure and Loading

92.160 x 96/100 x 240/256 x 1024/1152 x 8/1024 = 0.576 K

Frame Efficiency	Container Efficiency	Padding Efficiency	Codes/ Total Codes



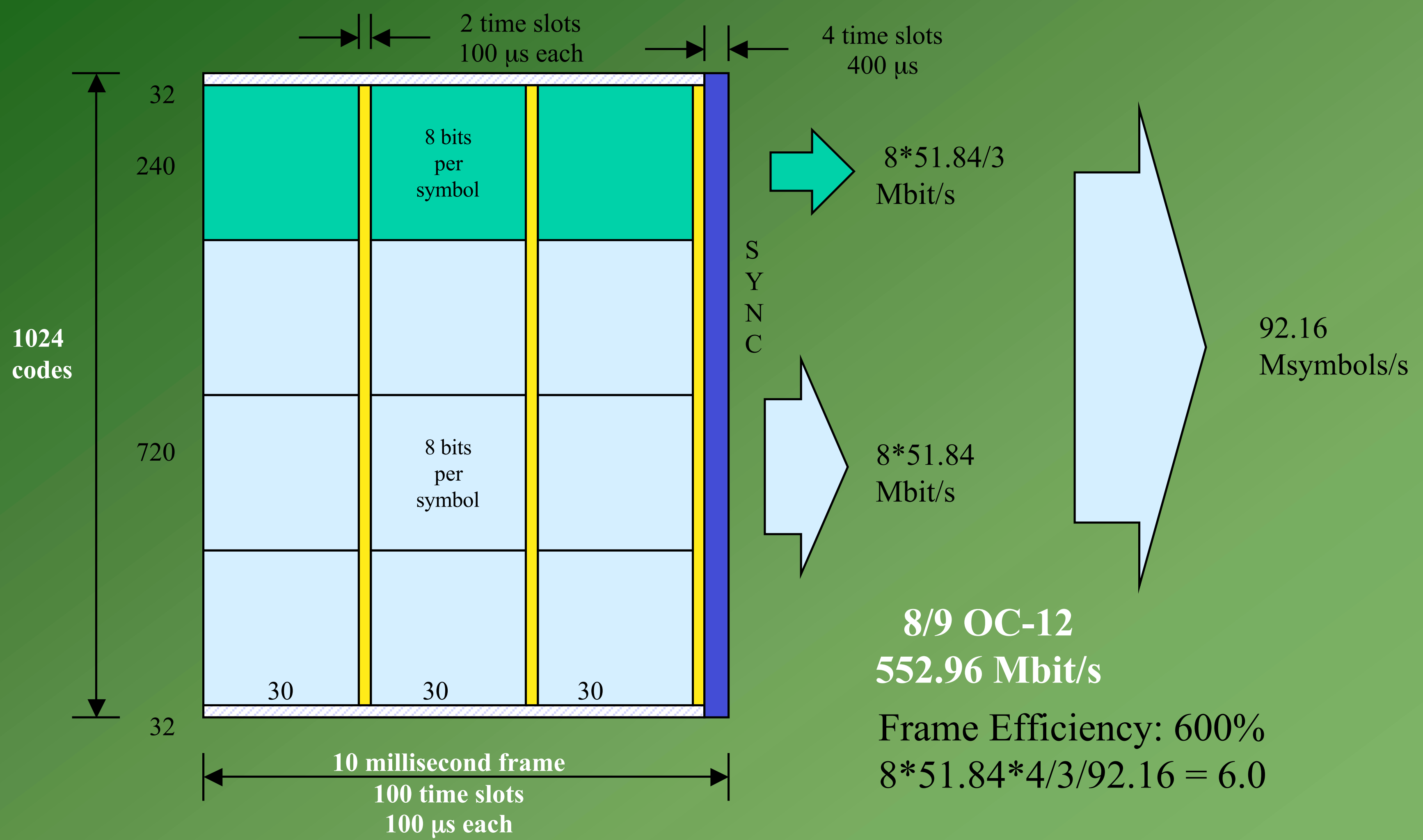
Frame Capacity with BPSK Modulation



4/3 OC-1
69.12 Mbit/s

Frame Efficiency: 75%
51.84*4/3/92.16 = 0.75

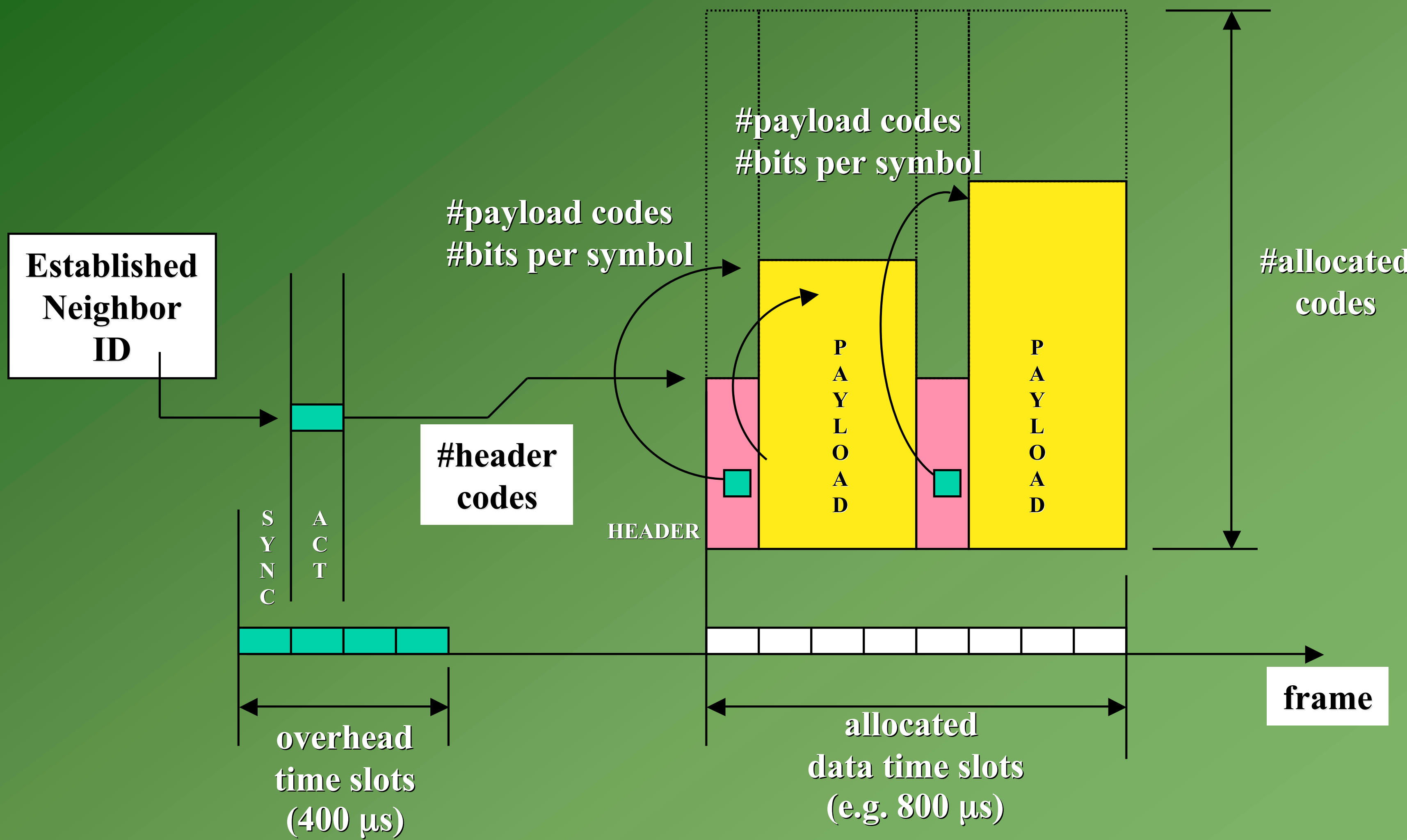
Frame Capacity with 256-QAM Modulation



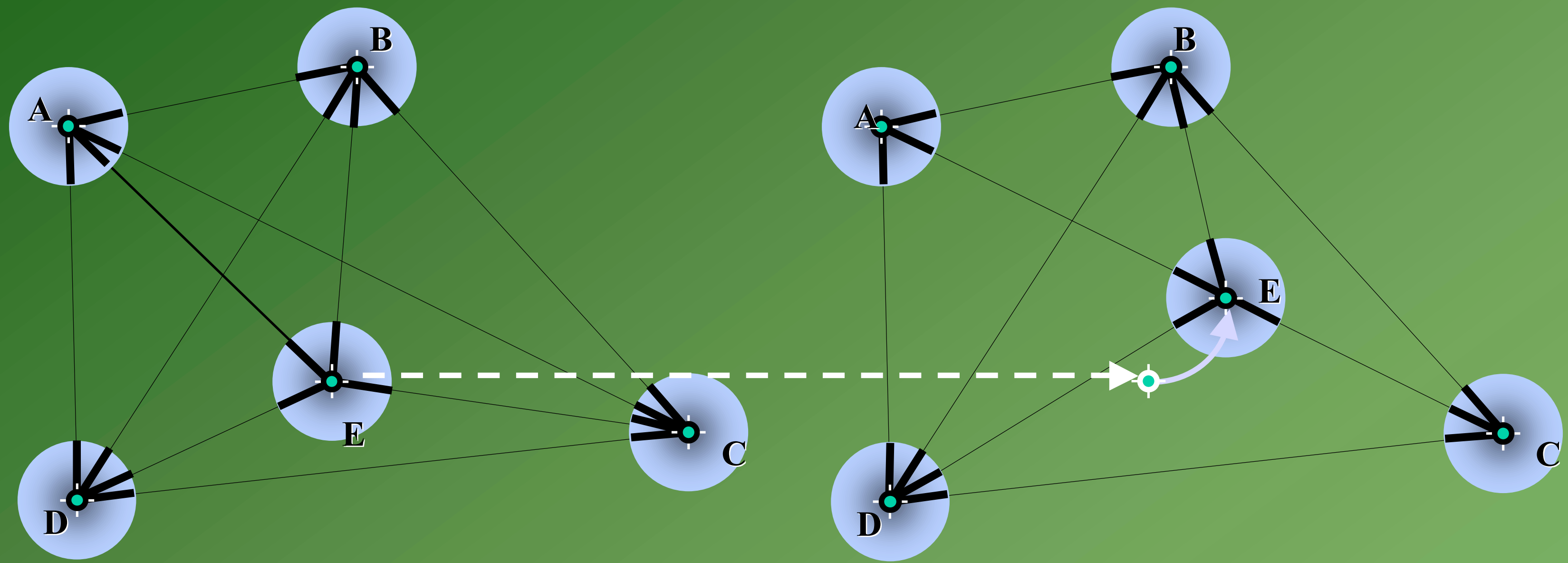
8/9 OC-12
552.96 Mbit/s

Frame Efficiency: 600%
8*51.84*4/3/92.16 = 6.0

Approach for transmission of packets with variable bit rates (without re-allocations) to satisfy mixed-application traffic delay/BER QoS requirements



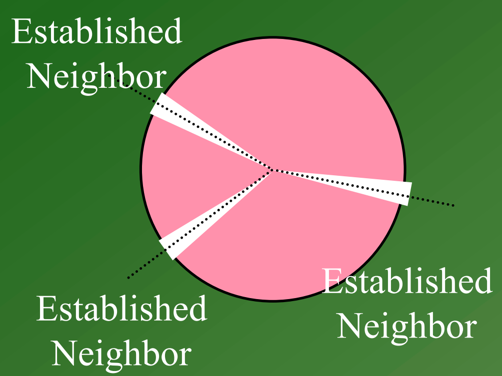
Example of topologies with spatially separated and spatially aligned links

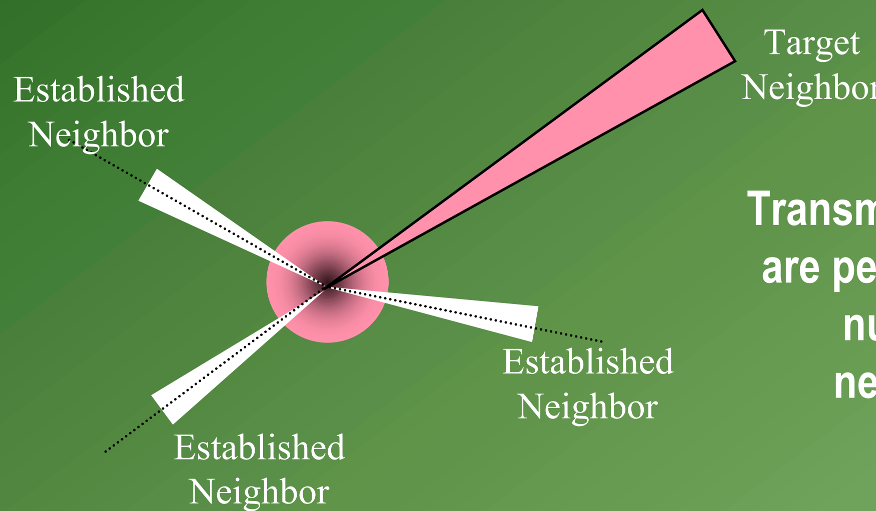


(a) - Topology with spatially separated links

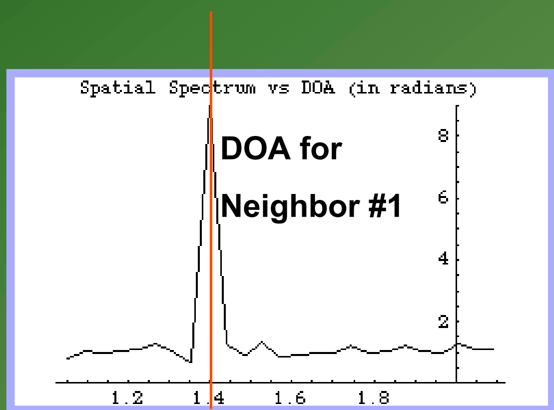
(b) - Topology with spatially aligned spacecraft

Systematic use of null-steering enables ad hoc space comms without interference

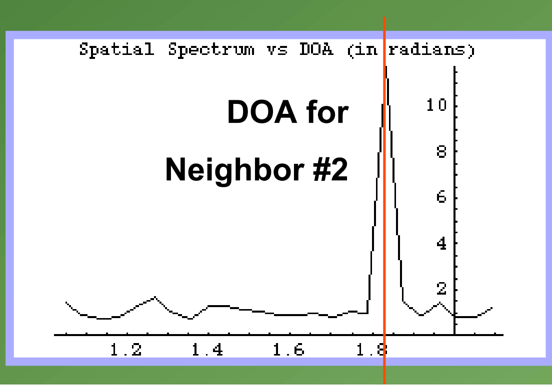




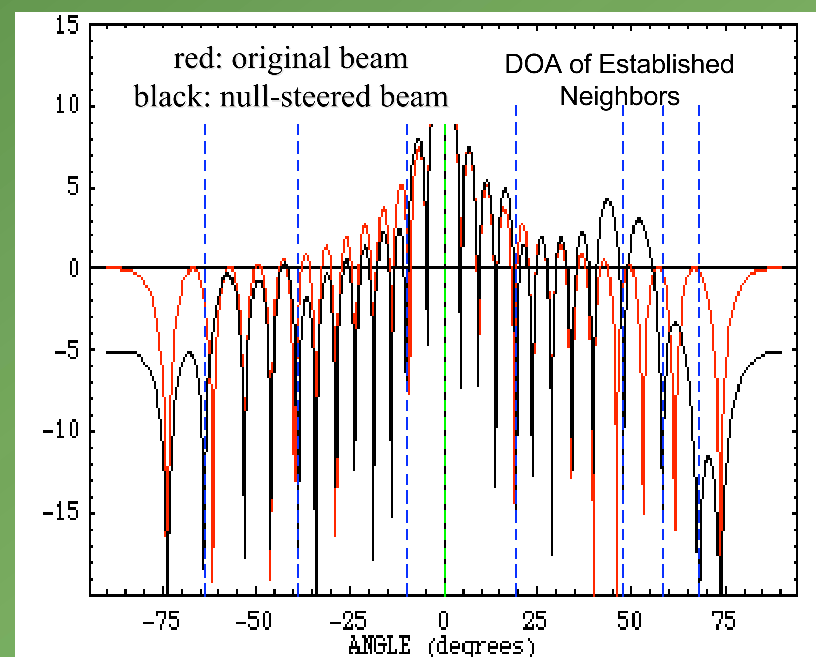
Transmission and reception are performed always with nulls to non-target neighbors to avoid interference



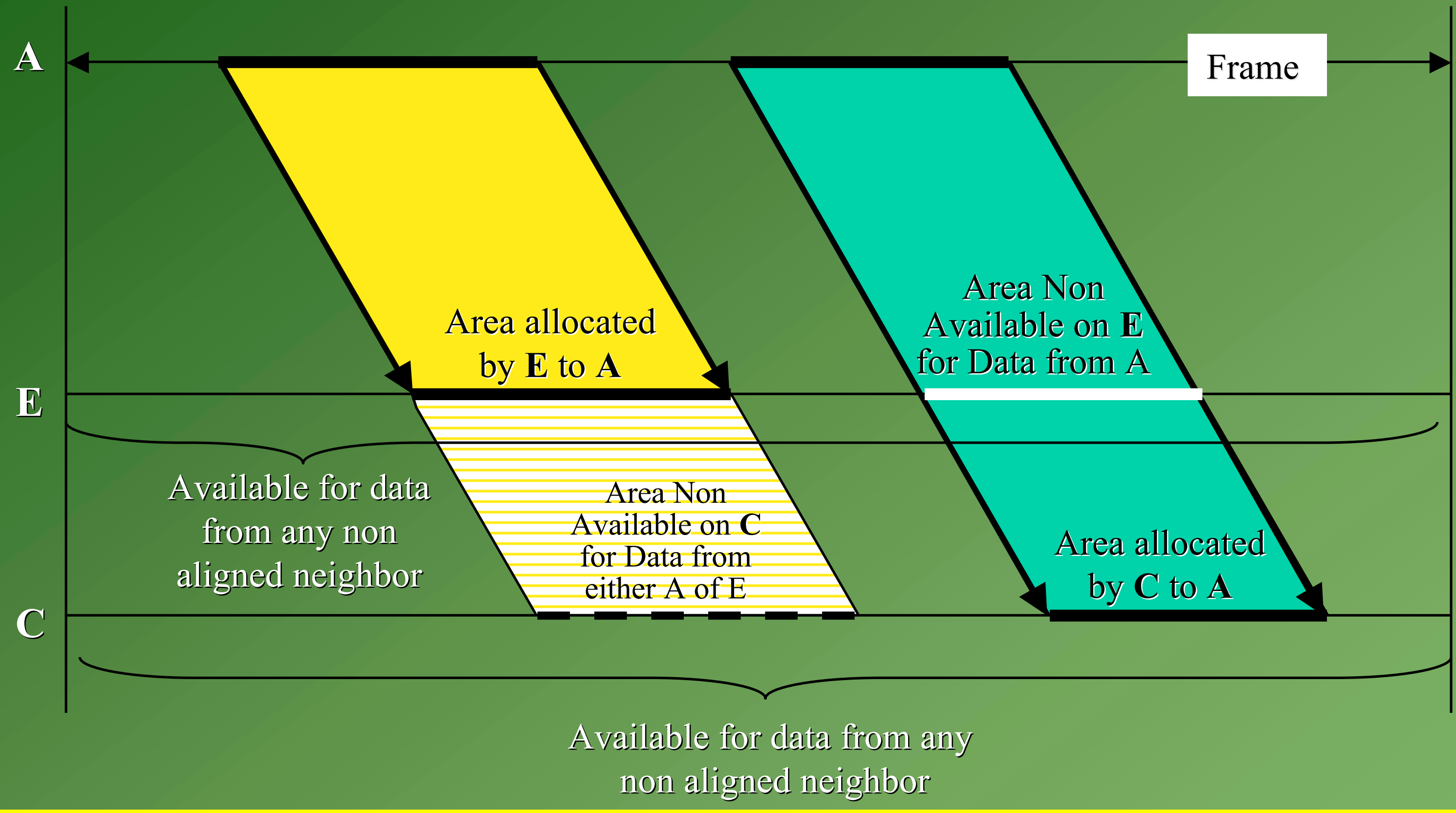
Angular directions are measured & updated periodically



Null-Steered Beam Generated Using Closest Zero Replacement Algorithm

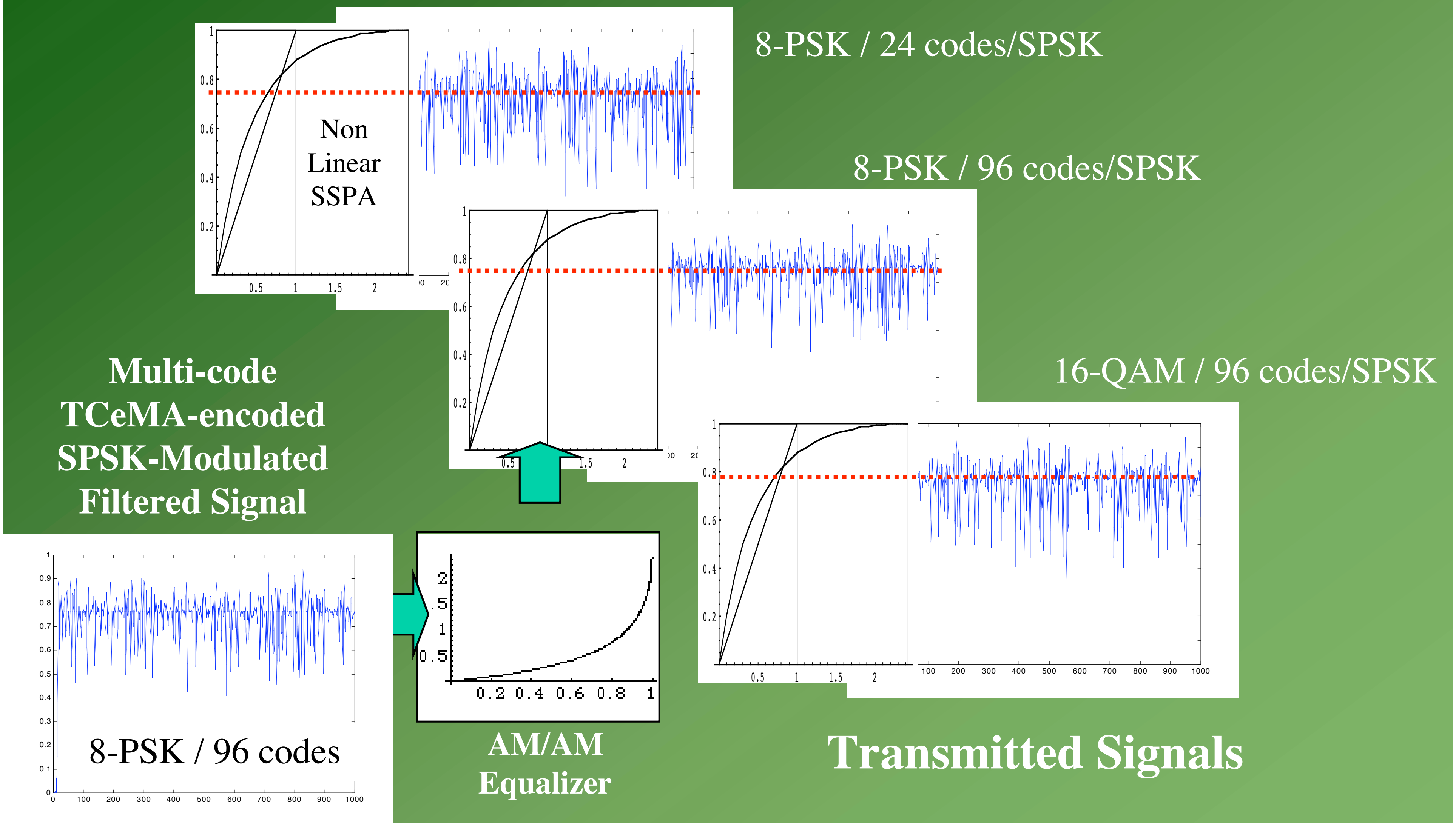


TDMA is used to work around non-intentional interference on spatially aligned links



The MAC protocol continuously tracks the relative spatial alignment and performs the time multiplexing negotiation among the aligned nodes to work around non-intentional interference

Split-Phase Shift Keying (SPSK) modulation enables transmission of null-steered beams with antenna array SSPAs operating at near saturation



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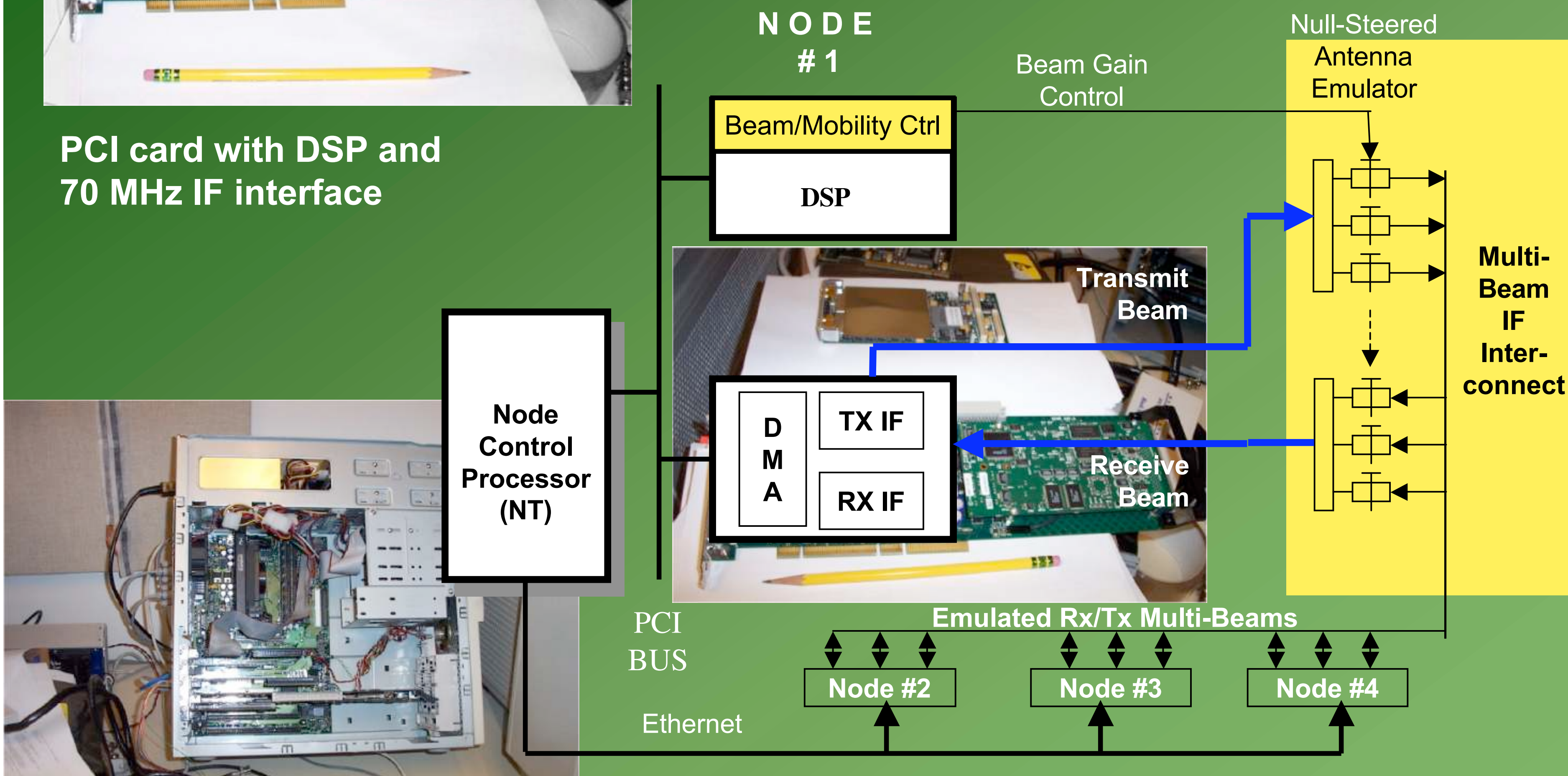
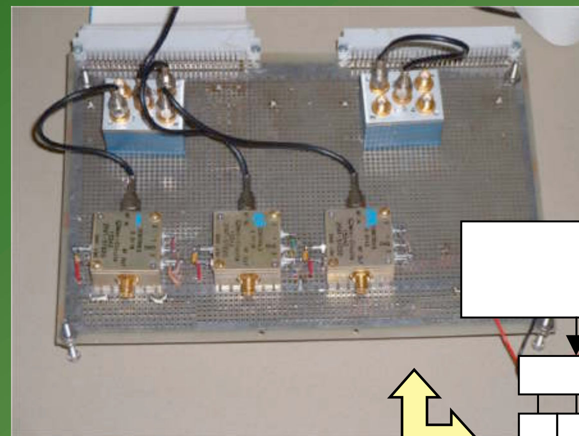
LABORATORY TESTBED: Used to verify the practical feasibility of integrating TCeMA with null steering

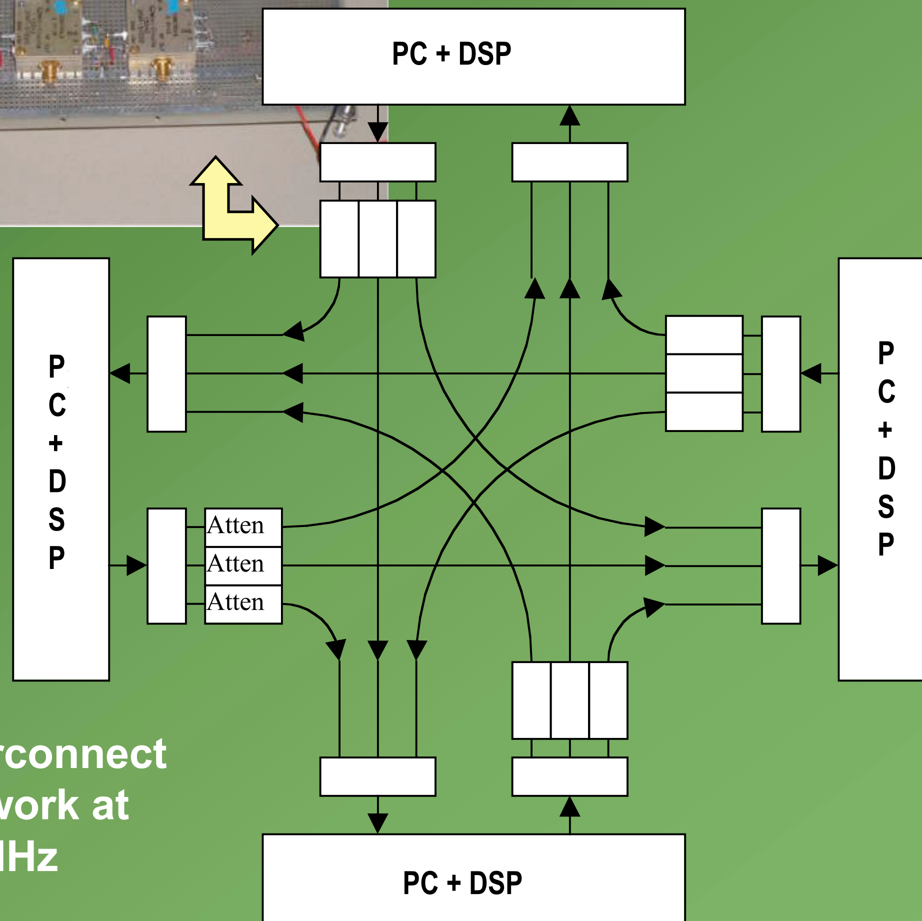
PCI card with DSP and 70 MHz IF interface



Null- steered antenna emulator and node interconnection at 70 MHz

Null-Steered Antenna Emulator implemented with splitters and DSP-controlled attenuators

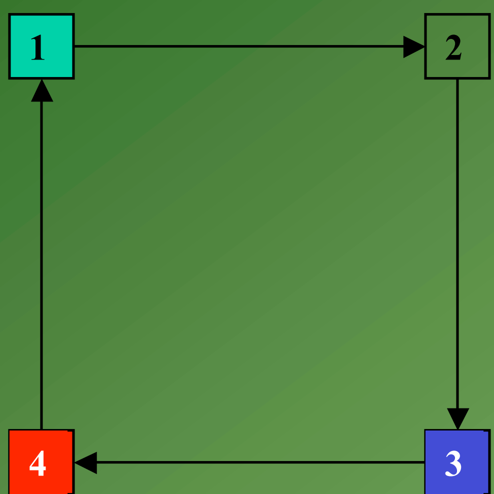




Interconnect Network at 70 MHz

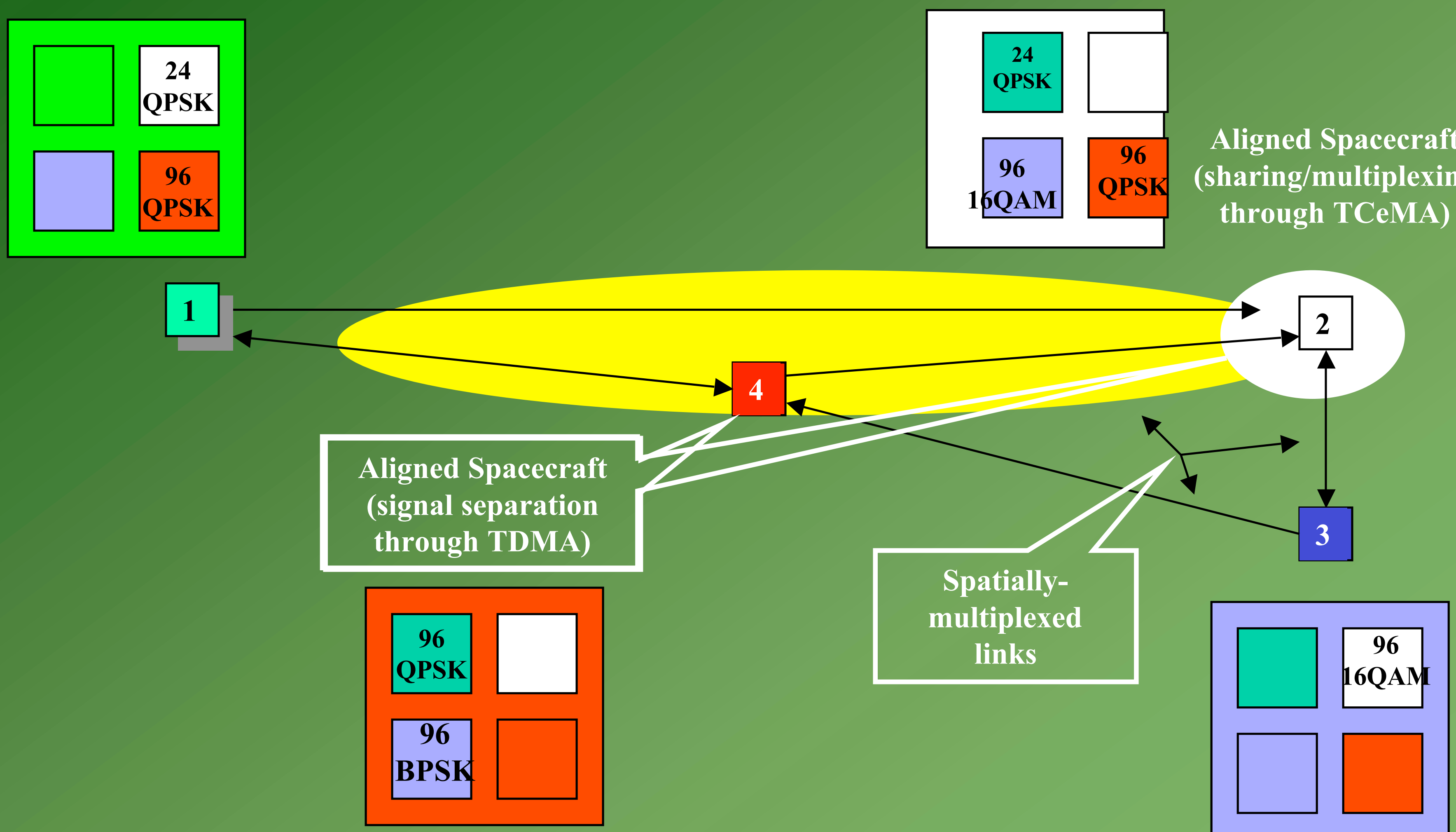
Lab Testbed Demo Scenario 1
Formation Flying

Star with a departing spacecraft



Loop

Lab Testbed Demo Scenario 2
Ad Hoc with Aligned Spacecraft

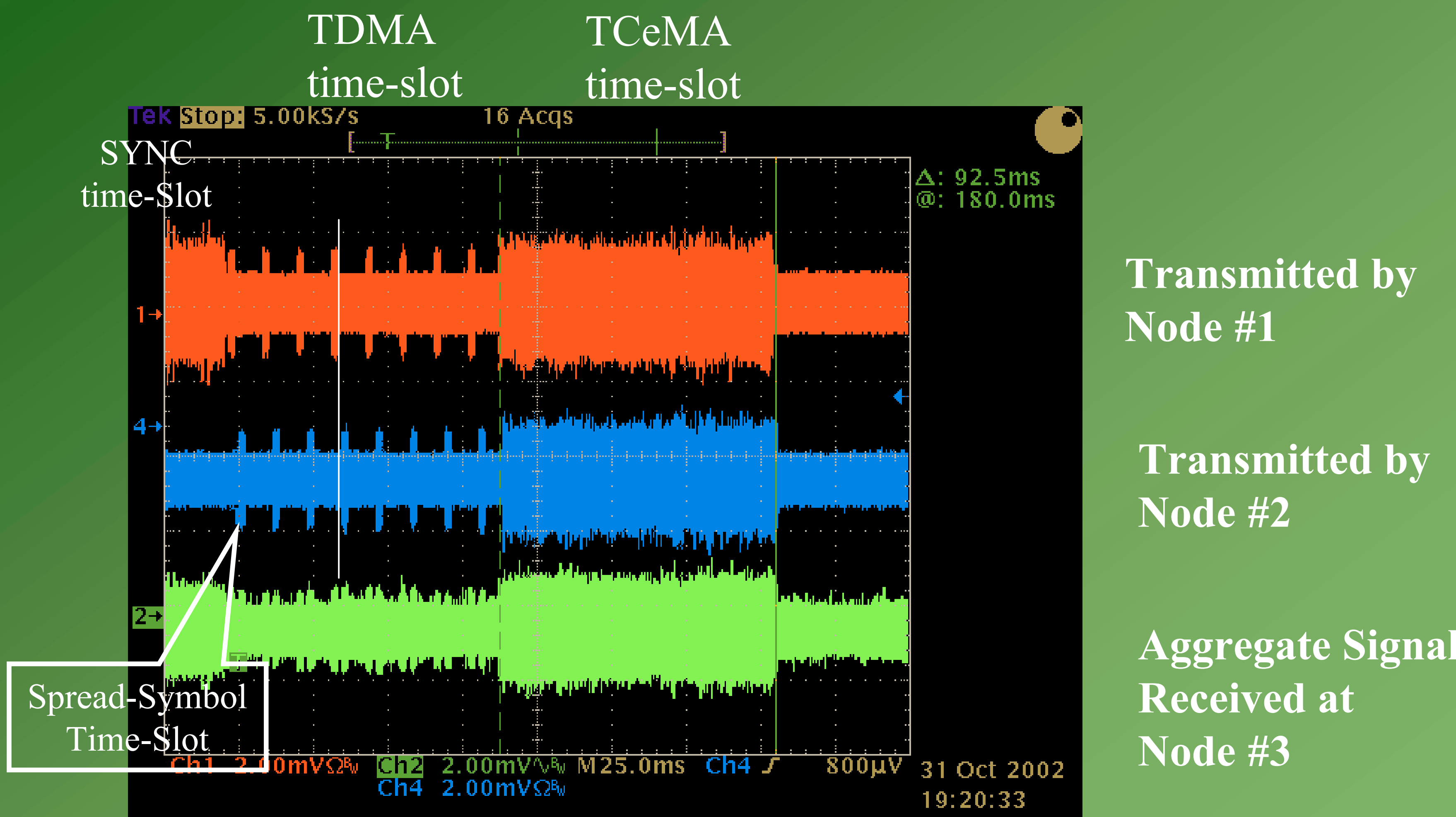


Lab/Demo Experiments

1. 3 nodes with code multiplexing + rx null-steering
2. Exp #1 + different distances between nodes
3. Exp #1 + large distance differential
4. Exp #1 + even larger distances + different rates + different modulations
5. 3 nodes + transition from non-aligned nodes (with spatial multiplexing) to aligned nodes (with code multiplexing)
6. 3 nodes and support for high data rates with spatial multiplexing
7. 4 nodes + time-code multiplexing + rx null-steering

All experiments were performed with
fixed-rate TDMA and variable rate TCeMA

Lab Testbed Typical Waveform Result: Side-by-Side Visualization/Comparison of Multiplexed TDMA and TCeMA Signals at 70 MHz

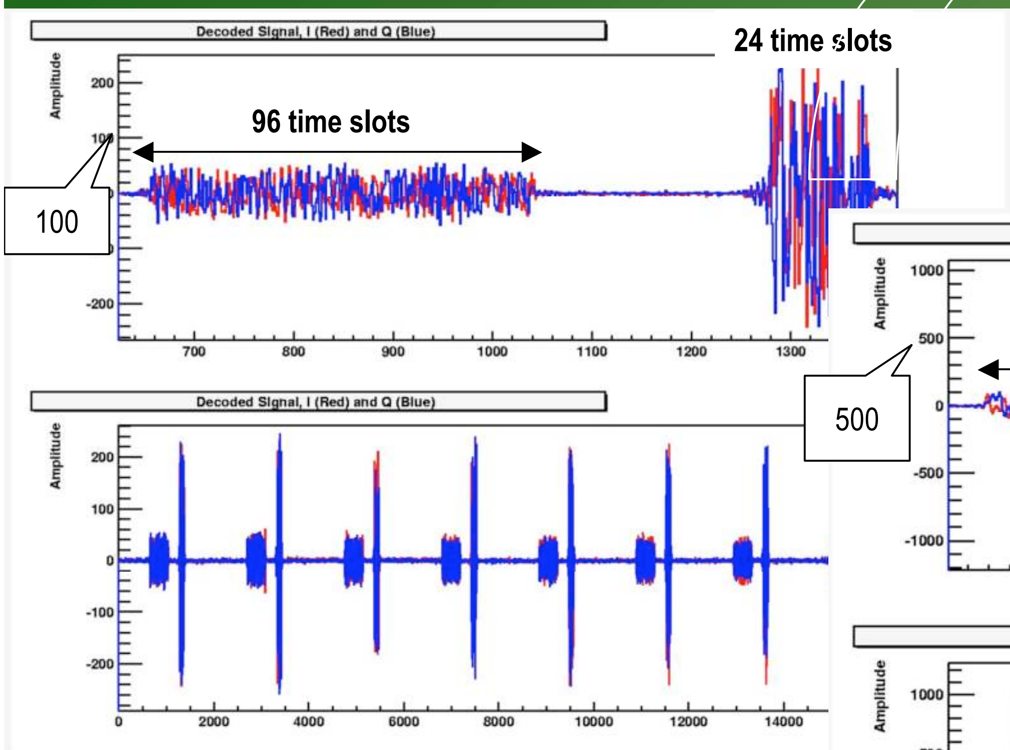


Lab Demo Typical Waveform Result #1

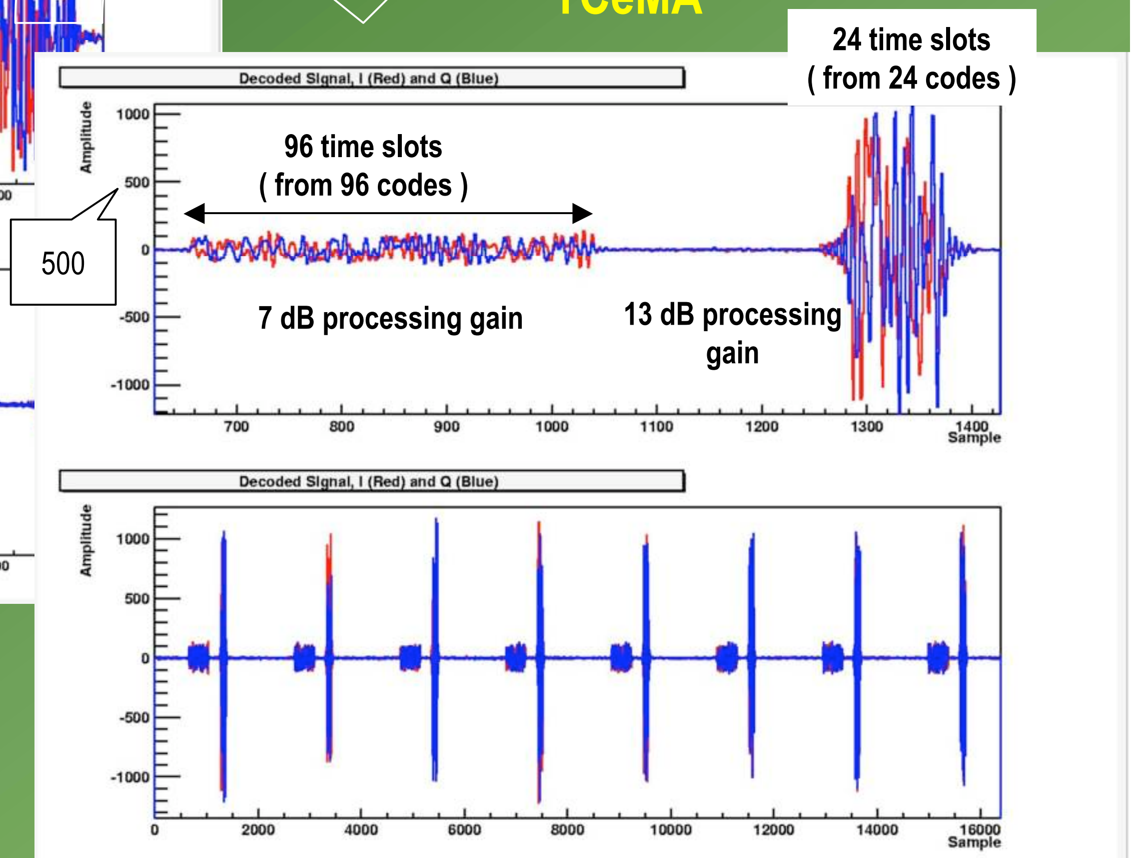
TDMA & TCeMA with Mixed Rates/Mixed Modulations

Node 2 Receiving from Nodes 1 and 3
Node 1 with 96 time-slots/QPSK Modulation
Node 3 with 24 time-slots/16-QAM Modulation

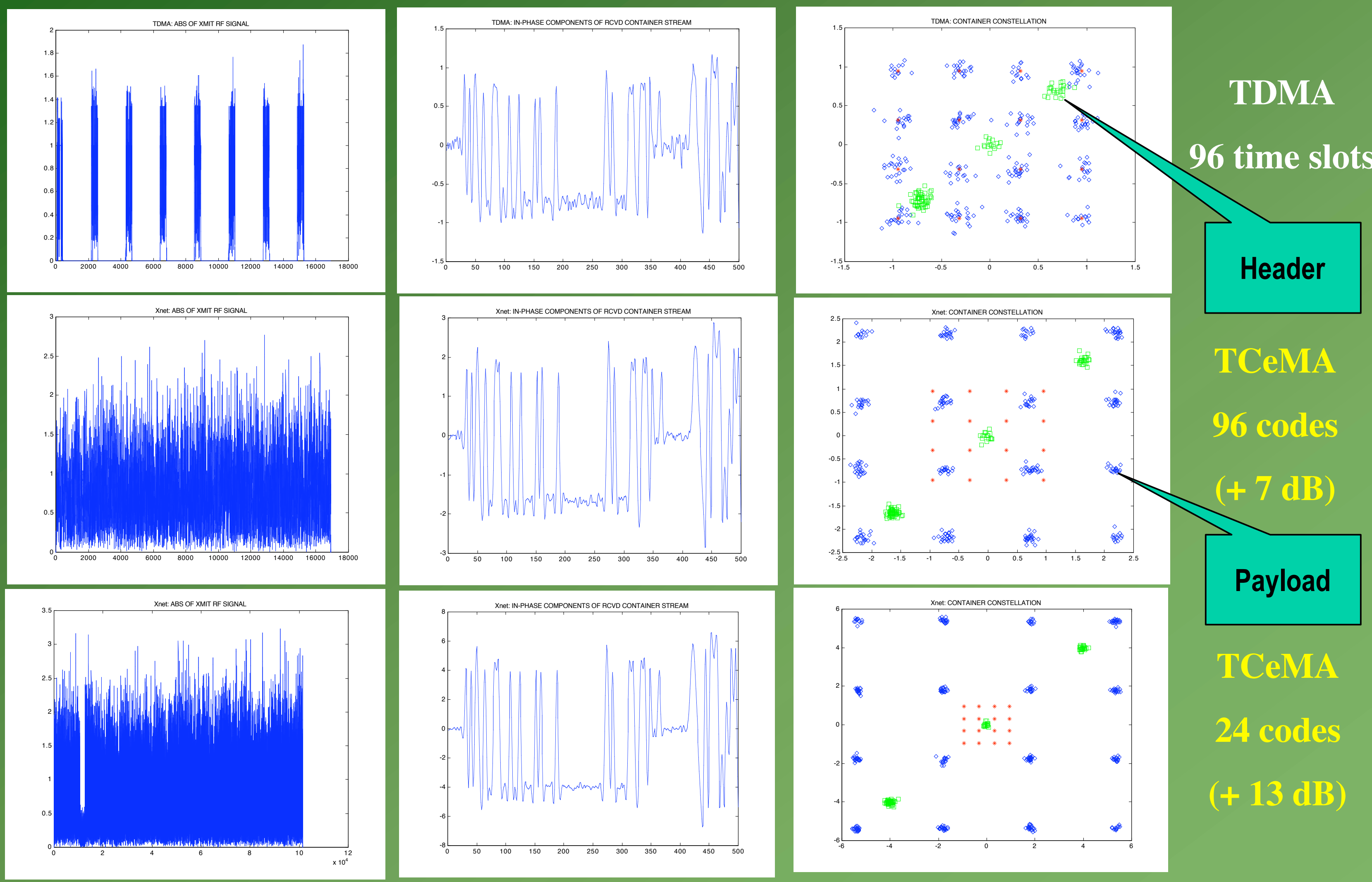
TDMA



TCeMA



Lab Demo of Typical SNR Improvement Enabled by the use of variable codes with TCeMA



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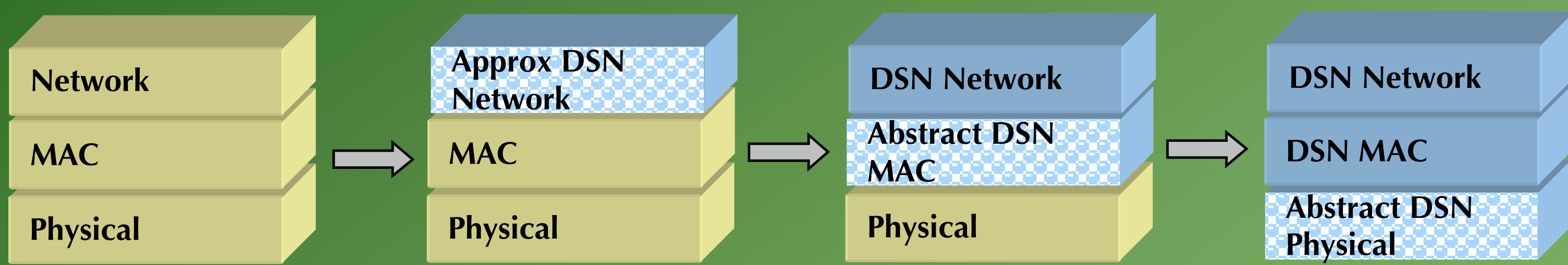
Modeling and OPNET Simulation Approach

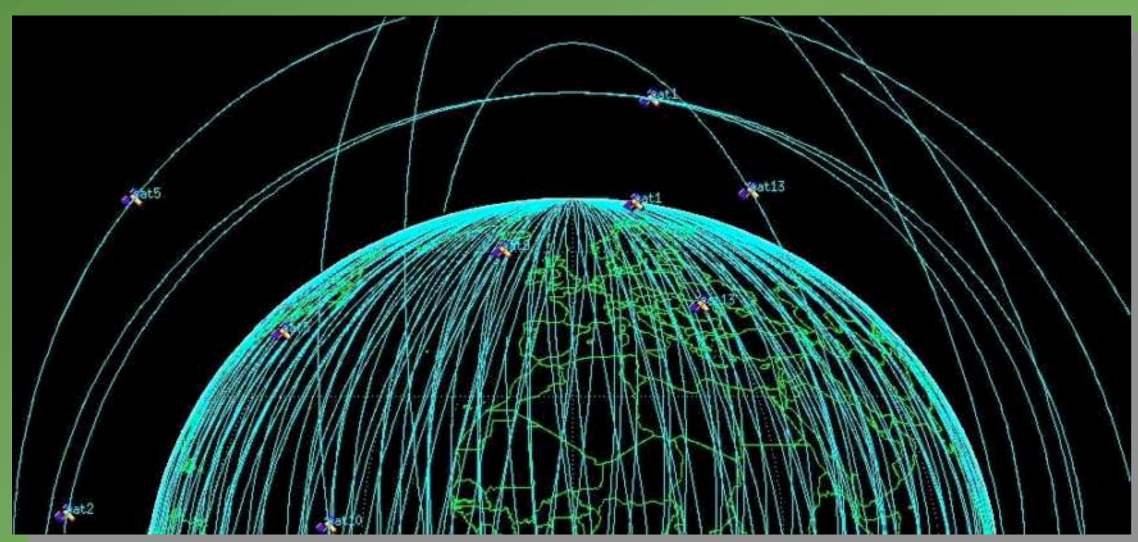
Start with legacy models from DARPA Ad Hoc Networking projects as baseline

- GloMo DAWN (Density and Asymmetry Adaptive Wireless Network)
- FCS UDAAN (Utilizing Directional Antennas for Ad Hoc Networking)

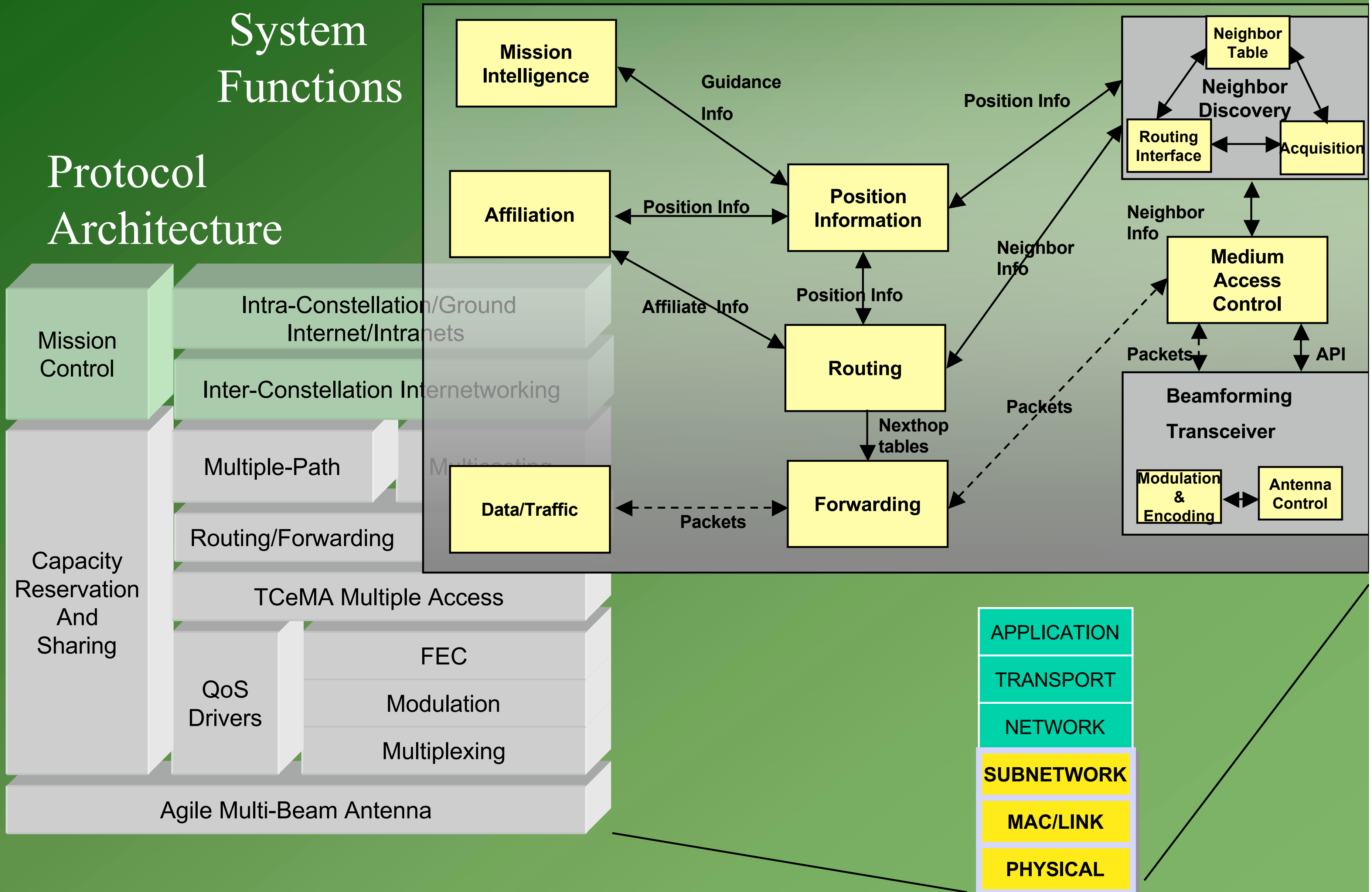
Then progressively refine the stack/modular architecture



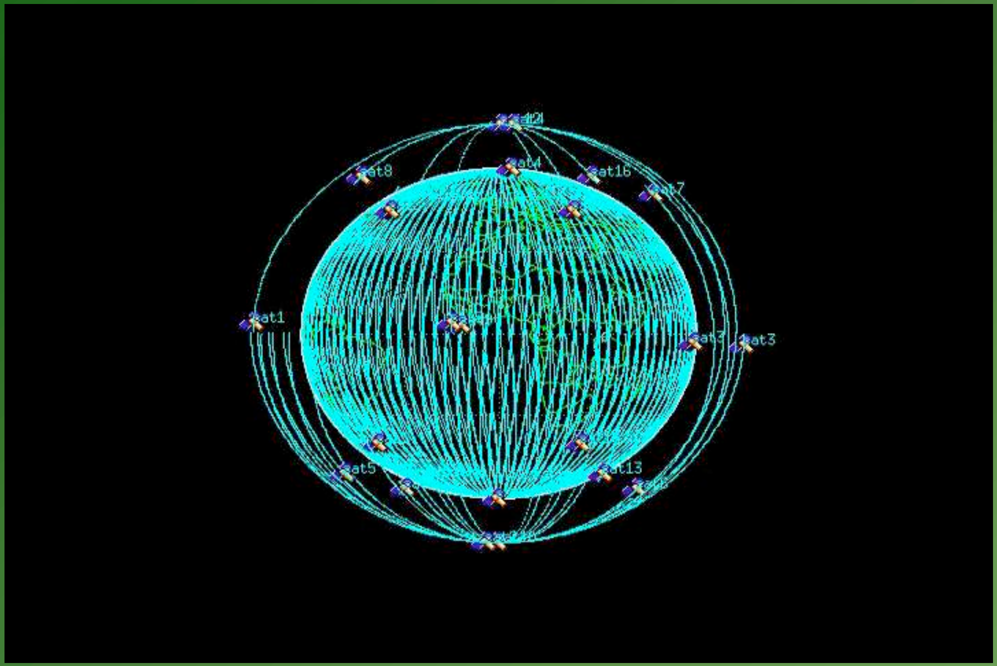
Use a multiple-altitude LEO/MEO/GEO constellation as a challenging environment for testing the system performance

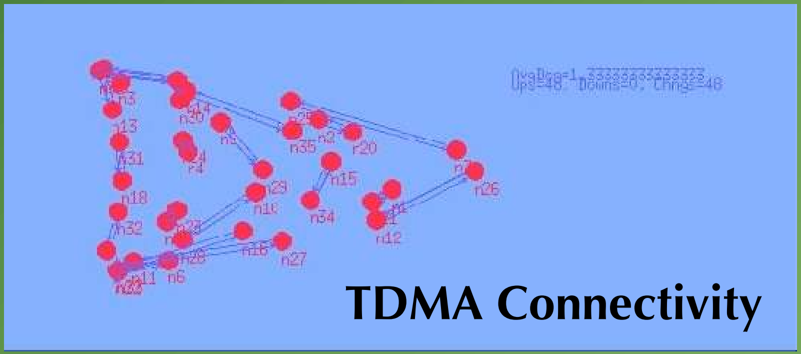


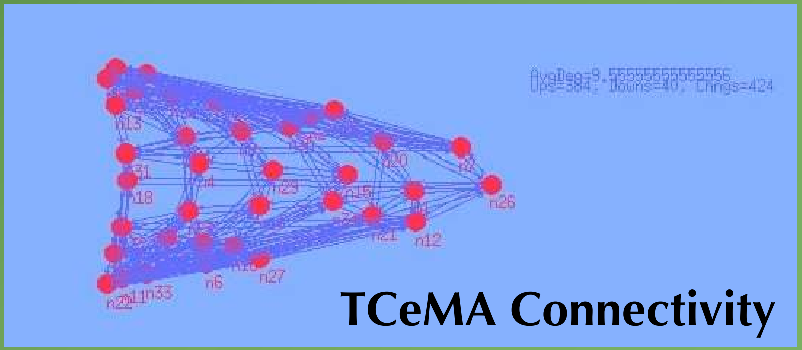
Protocol Architecture and System Functions



OPNET Model and Results



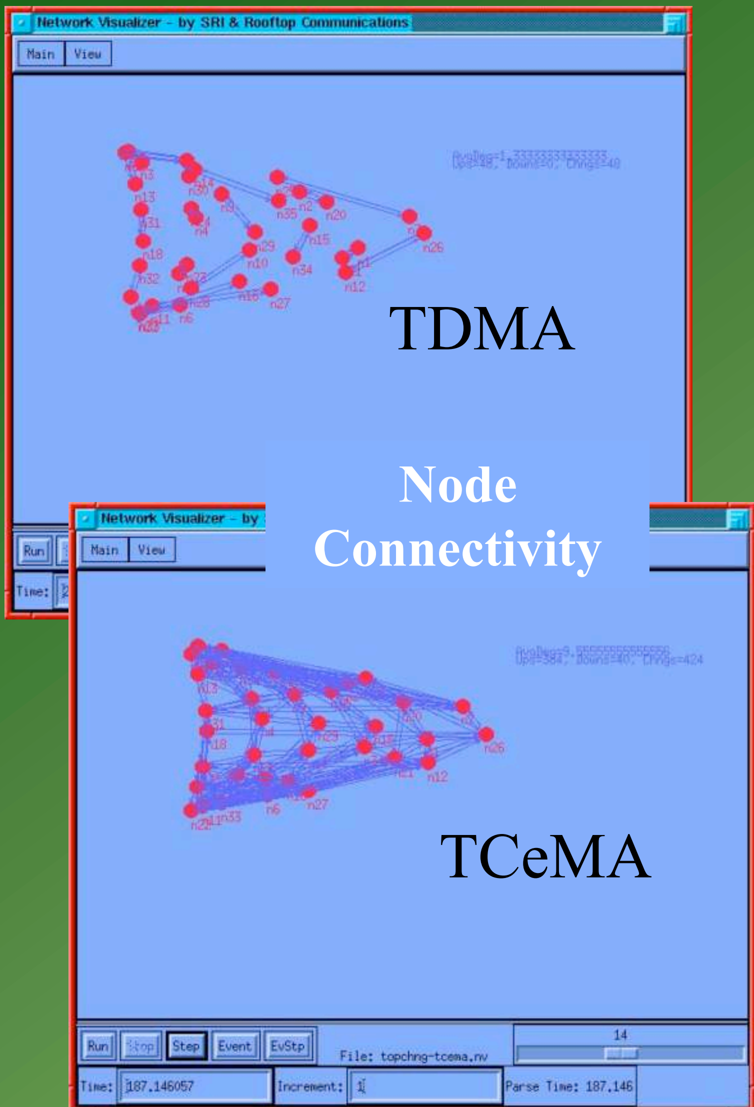


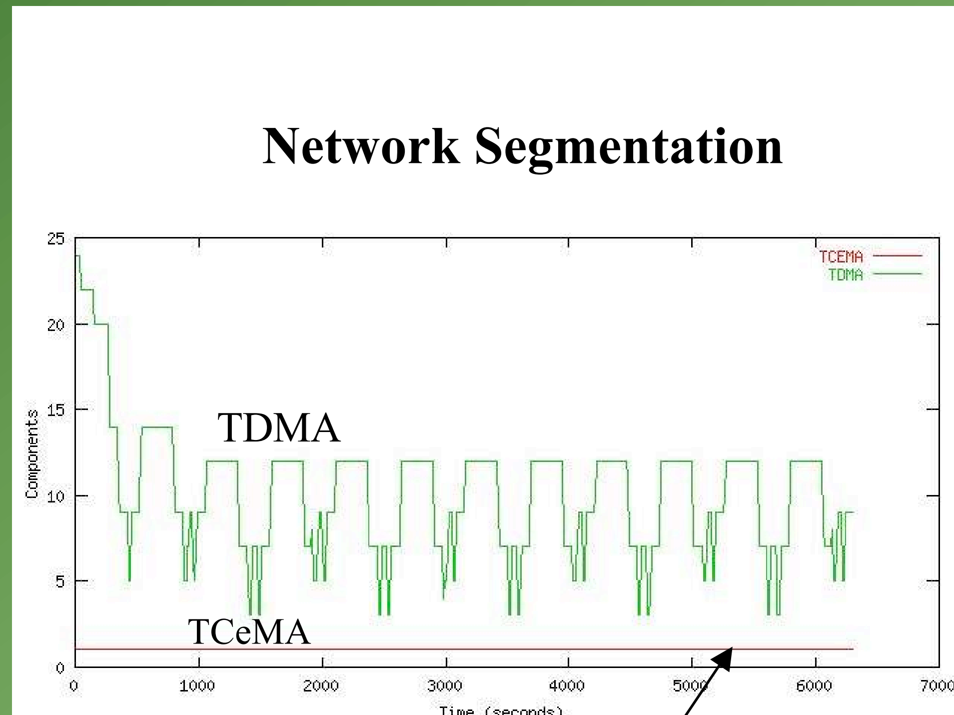


Parameters for LEO Constellation:

- 30 GHz with 100 MHz bandwidth. Transmission power 100 watts.
- 36 satellites in 6 polar orbits at 60 degrees apart with 6 satellites in each orbit.
- Orbit period 105 minutes (~1000 kilometers altitude).
- TDMA link: 100 Mbit/s or nothing
- TCeMA link: k * 100 Kbps, k=1… 1000 (k = number of codes)
  m * 100 Mbps, m = 1… 8 (2^m-QAM Modulation)

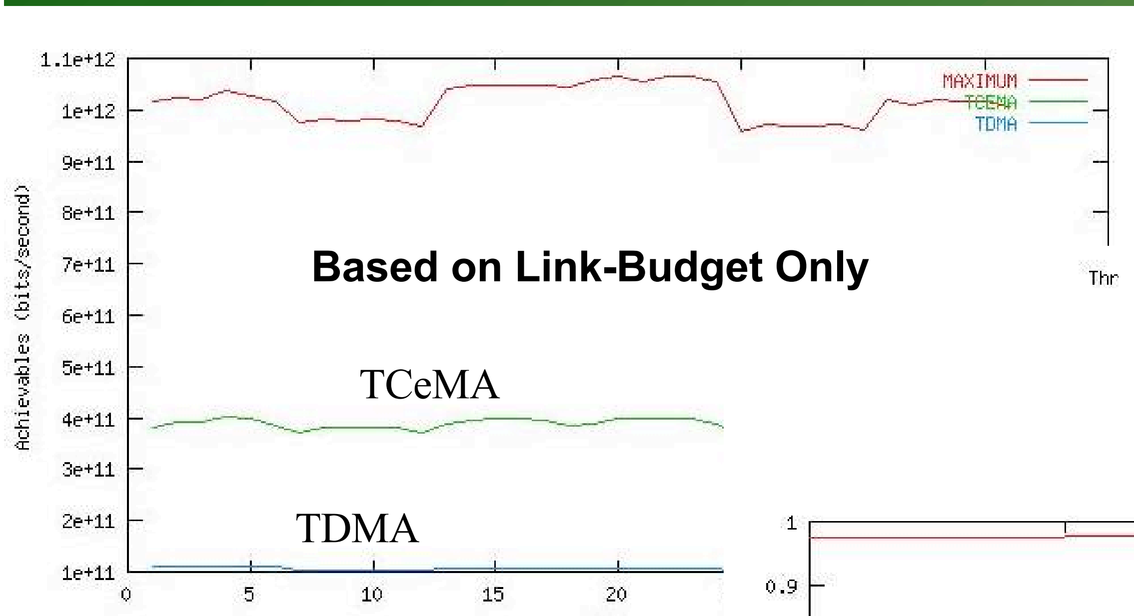
OPNET Simulation Results: Node Connectivity and Network Segmentation



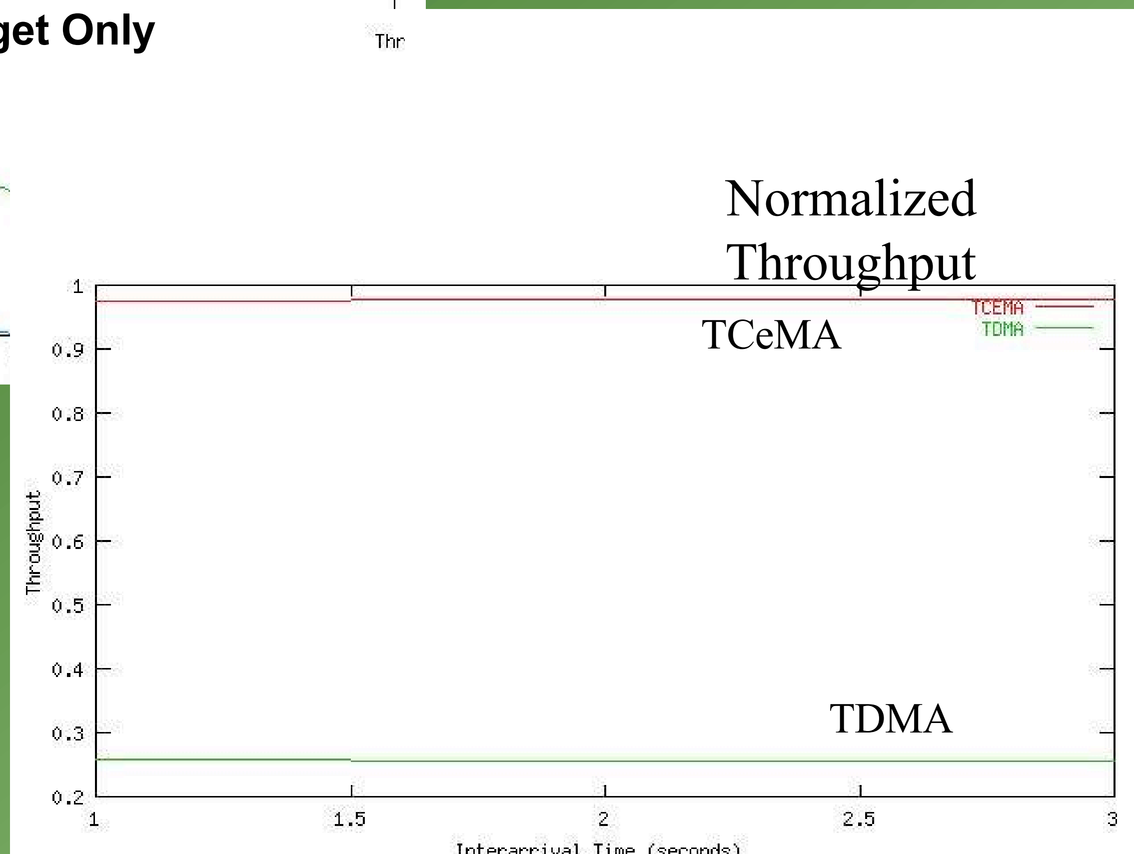


With TCeMA the network is always connected

OPNET Simulation Results: Network Aggregate Throughput



Node Number

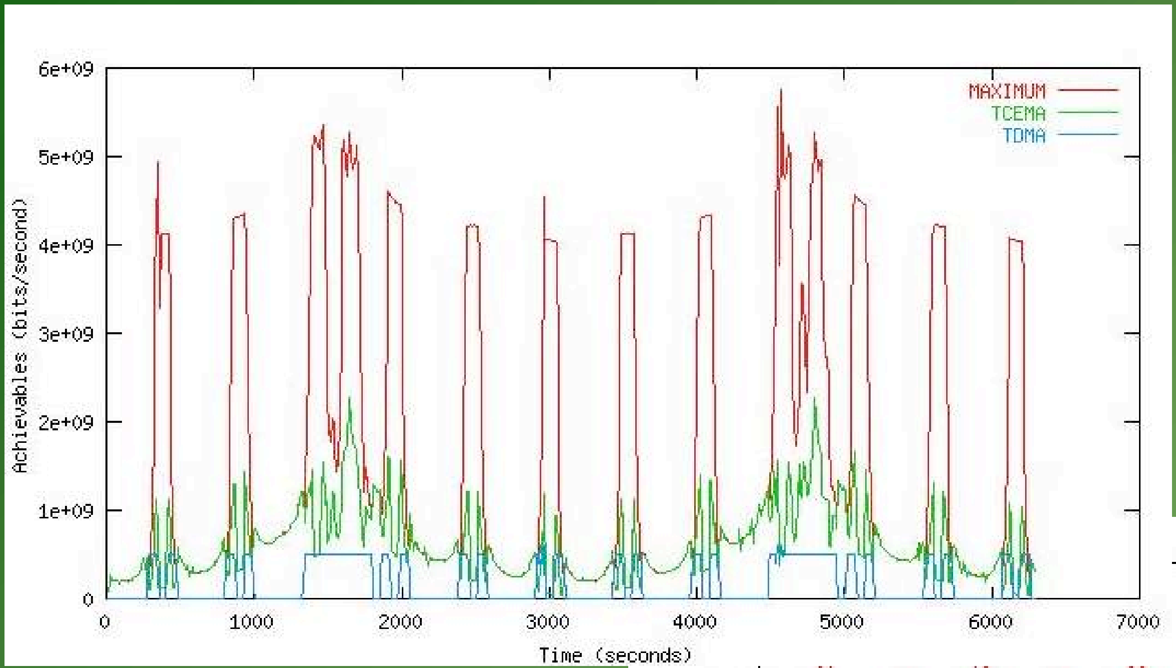


Packet Inter-arrival Time (ms)

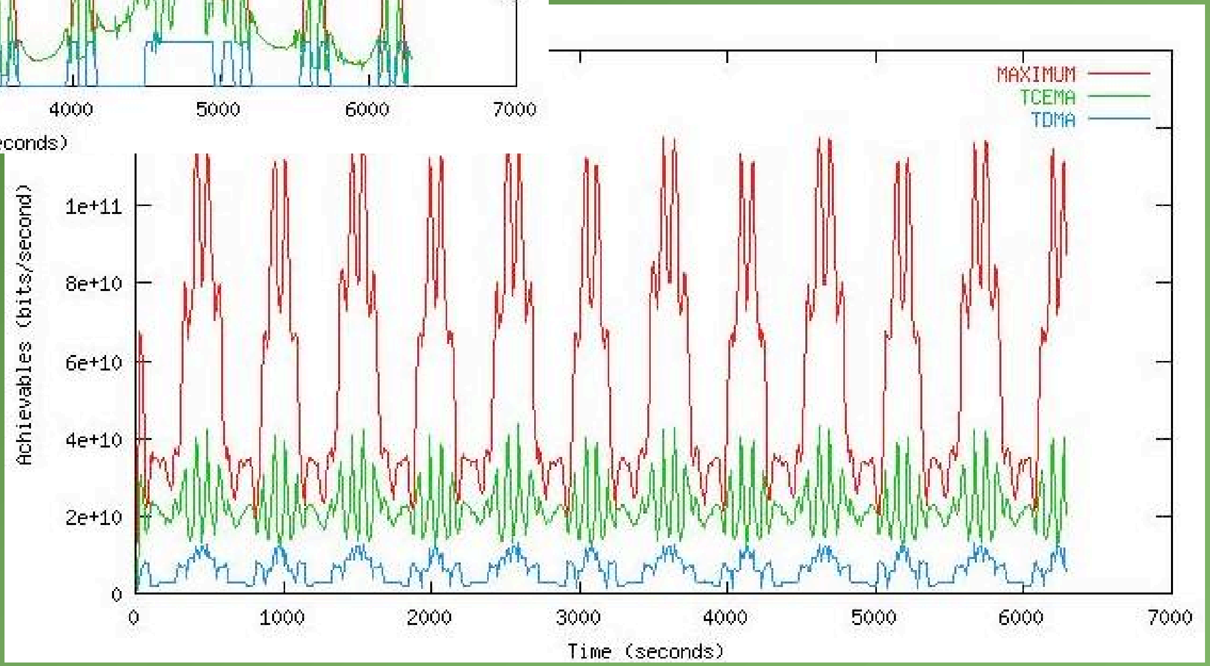
TCeMA clearly outperforms TDMA

OPNET Simulation Results: Aggregate Rate Over Time

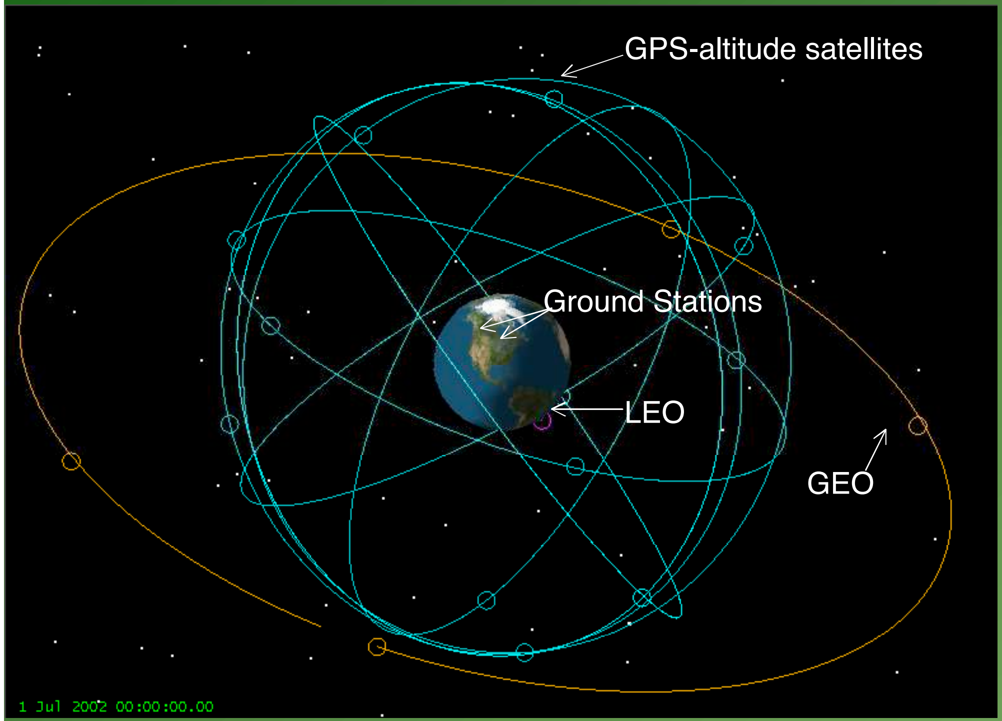
One Node



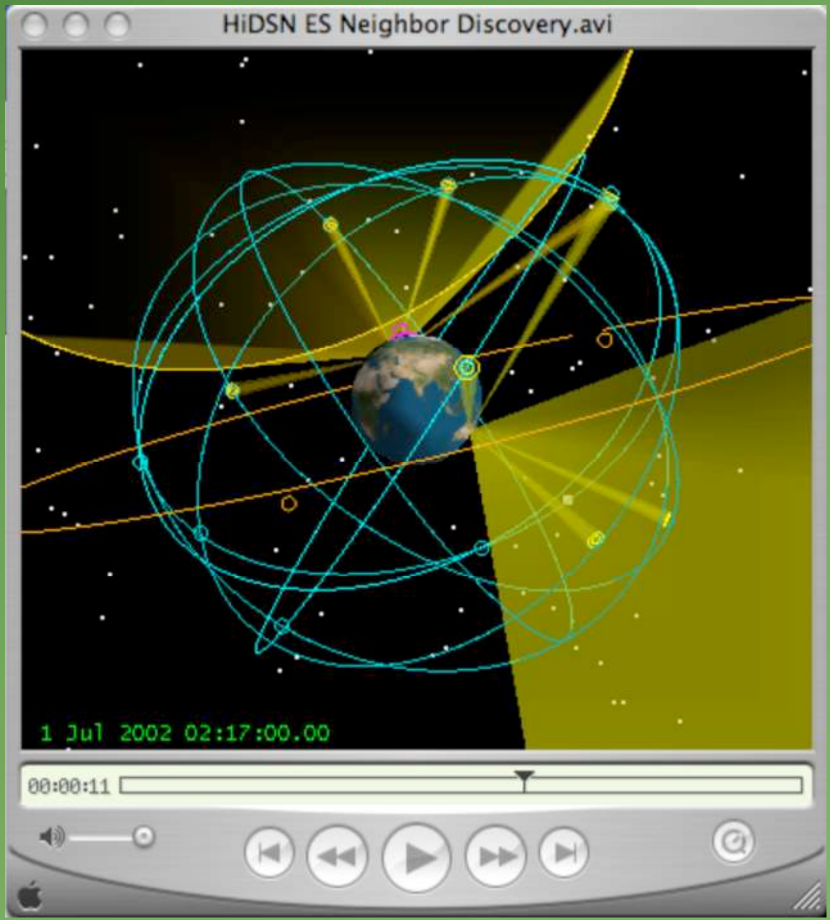
All Nodes



The "full-capability constellation" include nodes at ground NASA sites and spacecraft at LEO, GPS and GEO altitude orbits.



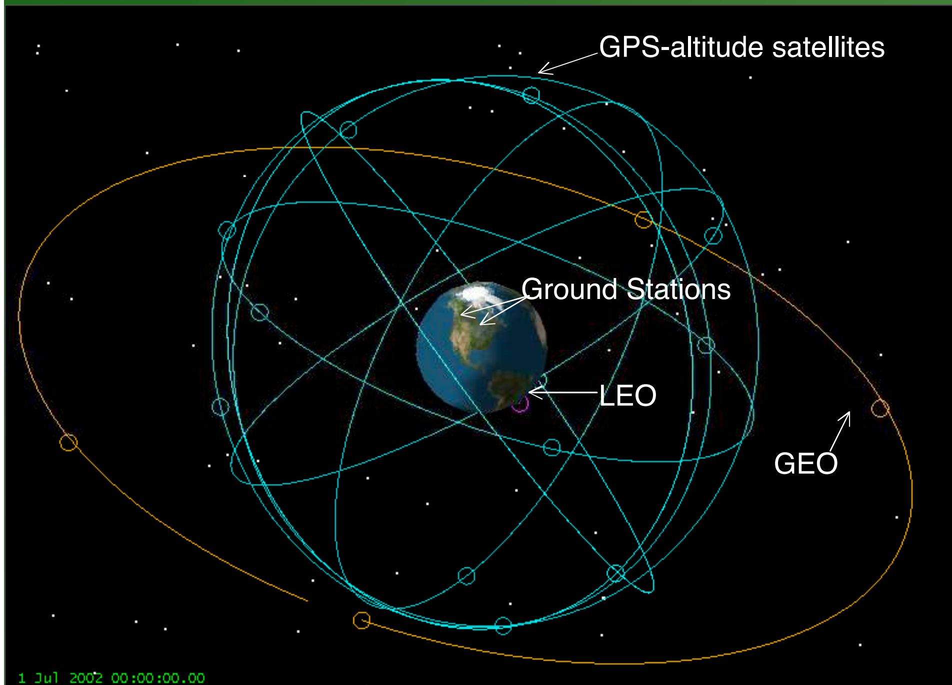
50-Node Constellation



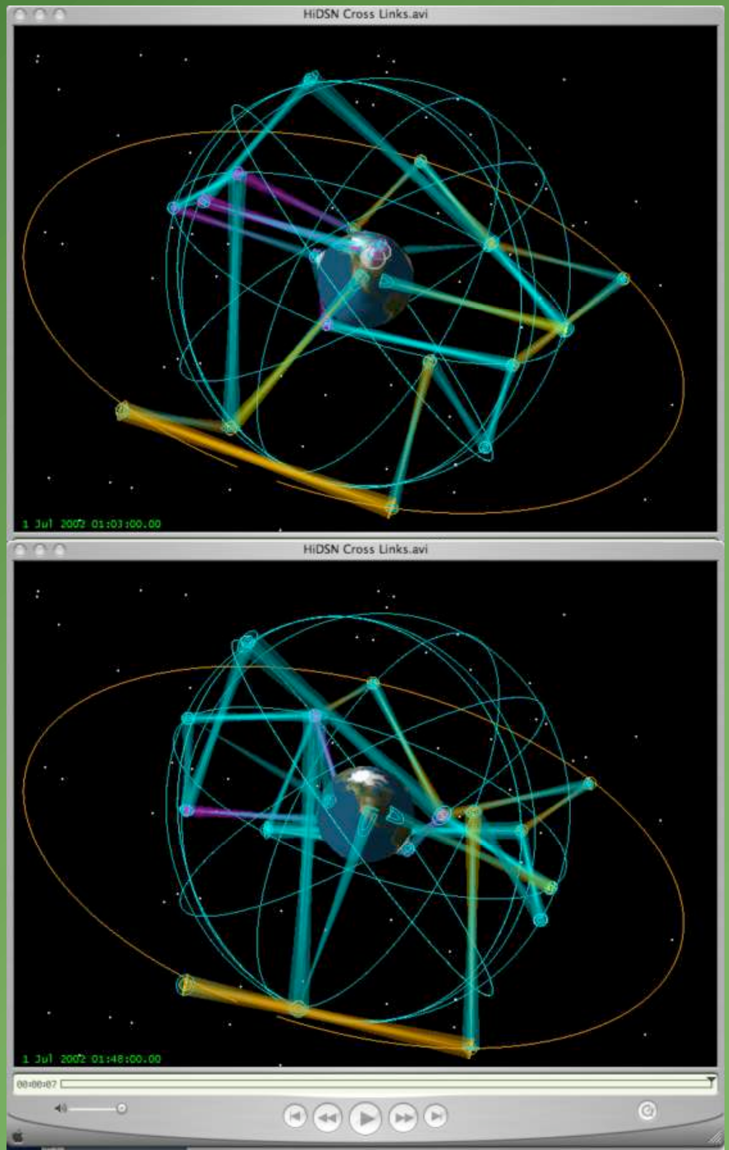
Dynamic Neighbor Discovery
(STK animation with OPNET generated data)

The "full-capability constellation" include nodes at ground NASA sites and spacecraft at LEO, GPS and GEO altitude orbits.

BBN TECHNOLOGIES



50-Node Constellation



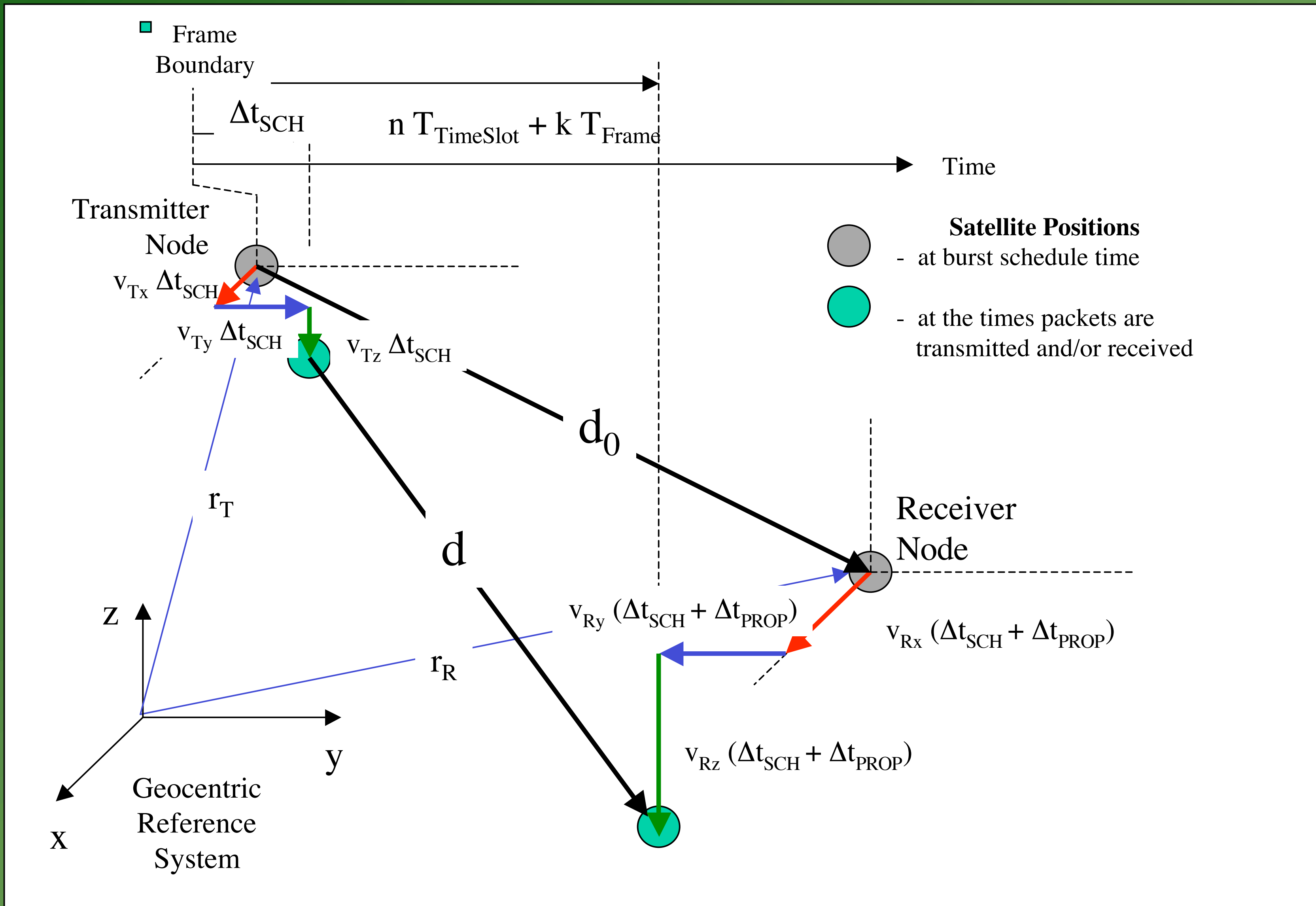
Dynamically Established Cross-Links
(STK animation with OPNET generated data)

50-Node OPNET Simulation

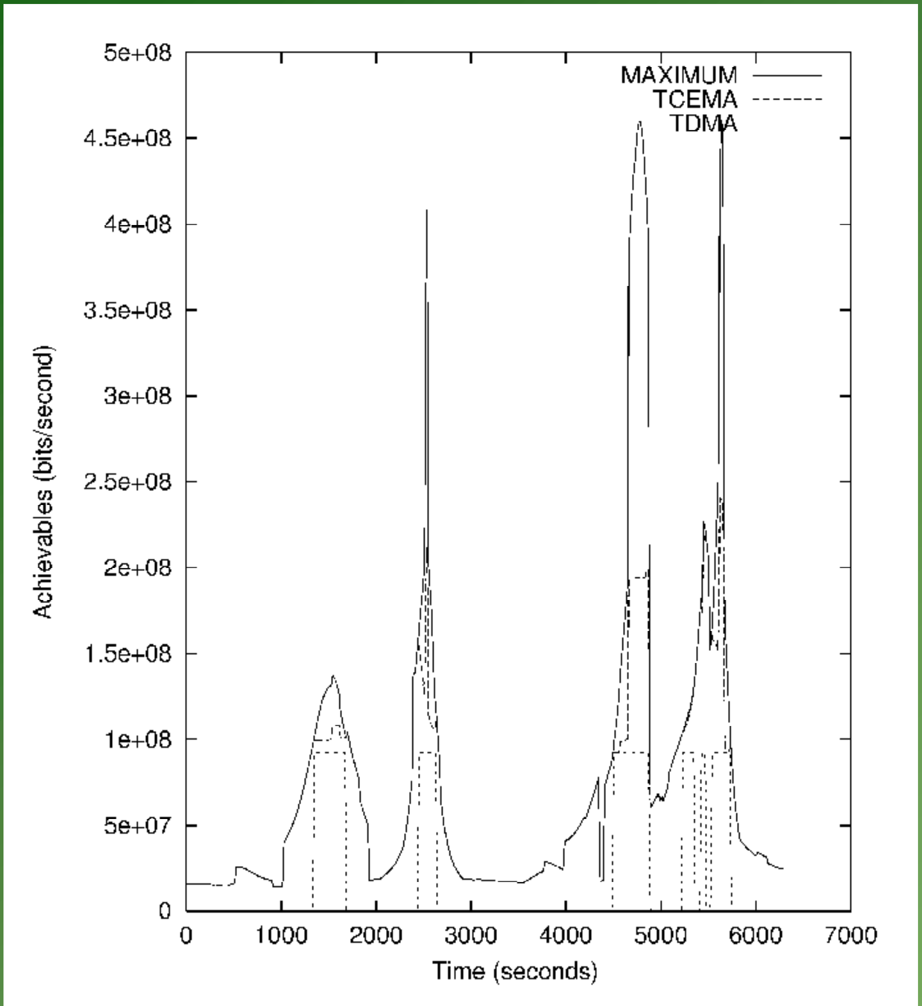
Table 7.1 Full-Capability Constellation

NASA LEO Satellites (21)	NASA GEO Satellites (7)	NASA Ground Sites (10)	GPS Satellites (12)
1 – ACRIMSAT	22 - TDRS_03	29 - Ames	39 - GPS_2-01
2 – ADEOS-2	23 - TDRS_04	30 - Glenn	40 - GPS_2-09
3 – AQUA	24 - TDRS_05	31 - Goddard	41 - GPS_2-11
4 – EO-1	25 - TDRS_06	32 - Guam	42 - GPS_2-13
5 – GRACE	26 - TDRS_08	33 - Johnson	43 - GPS_2-16
6 – GRACE-2	27 - TDRS_09	34 - JPL	44 - GPS_2-17
7 – ICESAT	28 - TDRS_10	35 - Kennedy	45 - GPS_2-20
8 – JASON-1		36 - Langley	46 - GPS_2-21
9 – LANDSAT_01		37 - Marshall	47 - GPS_IIR-02
10 – LANDSAT_02		38 - WhiteSands	48 - GPS_IIR-03
11 – LANDSAT_03			49 - GPS_IIR-06
12 – LANDSAT_04			50 - GPS_IIR-08
13 – LANDSAT_05			
14 – LANDSAT_07			
15 – ORBVIEW-01			
16 – ORBVIEW-02			
17 – ORBVIEW-03			
18 – QUIKSCAT			
19 – SORCE			
20 – TERRA			
21 – TRMM			

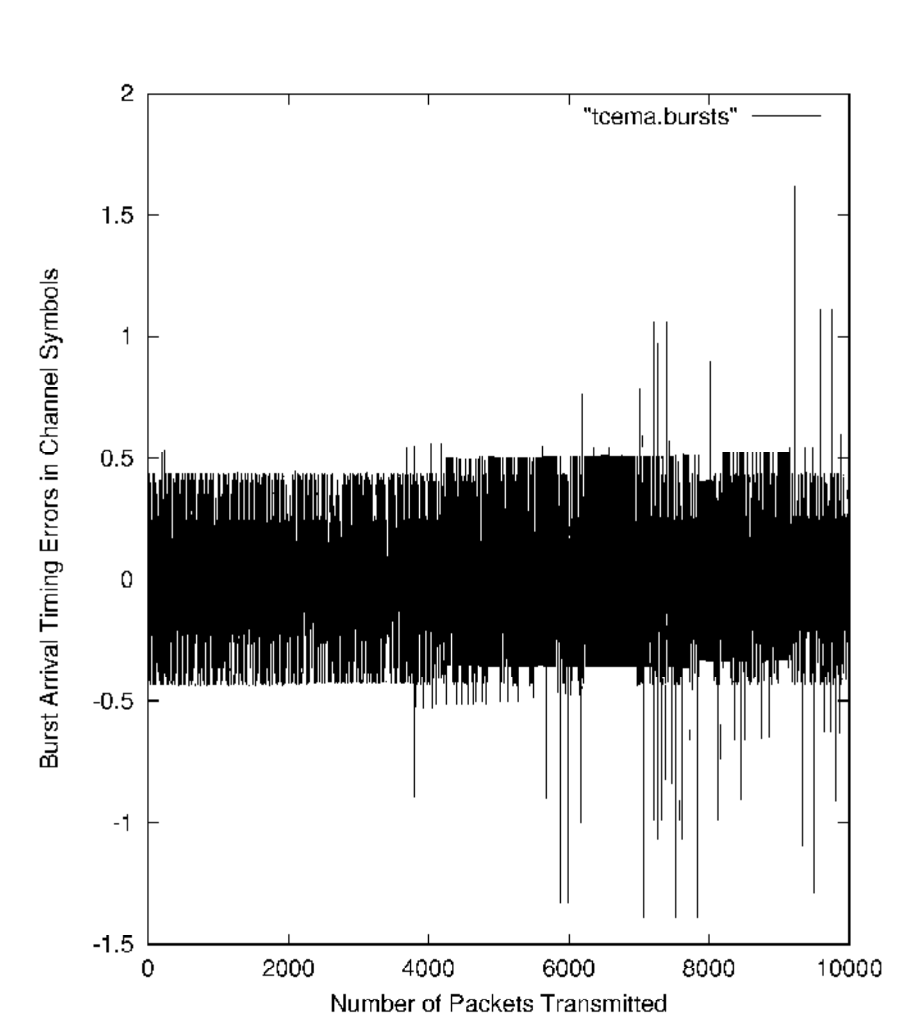
Burst Transmission Time Synchronization



Typical OPNET Simulation results (cont)



Typical-Node Burst Rate Over Time with TDMA and TCeMA



Typical-Node Burst Synchronization Uncertainty Over Time

Topics

- Network overview
  - How we find neighbor spacecraft
  - … close the link at high data rates
  - … reuse the spectrum multiple times over
  - … integrate time-code and spatial multiplexing
- System Architecture & Key PHY and MAC-layer Technologies
- Lab Testbed and Results
- OPNET Simulation and Results
- Summary of Project Results
- HiDSN Follow-on =>> ESTO's SpaceVPN focused on
  - Integration with the terrestrial Internet
  - IPSec-secure experimenter access to on-board instruments

Project Results

- *Comprehensive Architecture* for self-forming spacecraft & aircraft networks that can be customized to specific NASA missions, extended to include access by planetary platforms
- *Novel Physical-Layer Technology* – handles large differential range and delays, transmission power efficiency, and varying relative mobility
- *Novel MAC-Layer Technology* – handles multiplexing of varying-rate signals with varying/extreme power level differences, non-interfering inter-spacecraft transmission, network connectivity
- *Novel Neighbor Discovery Protocol* – "works" with space distances, measures neighbor location and achieves initial time & frequency synchronization
- *Novel Steady-State Synchronization Protocol* – maintains space-time-frequency synchronization, measures actual spatial isolation of received signals
- *Novel Network-Wide Synchronization Protocol* – maintains a common time-base across the whole network

Project Results (cont.)

- *A Packet Forwarding Technology* that explorers spatial multiplexing at its fullest, achieves order-of-magnitude greater aggregate throughput and connectivity than what is possible with conventional approaches
- *A Decentralized Routing Protocol* adapted to space distances and variable-rate connectivity that maintains, at each node, information about the active links and determines, for each destination, the next-hop to reach that destination.
- *A Laboratory Prototype Network* used to verify the practical feasibility of the time-code-spatial multiplexing technology (called TCeMA), perform comparisons with conventional technologies (e.g., TDMA)
- *OPNET Simulations* used to verify the scalability and the performance of the developed protocols when applied to large LEO networks, perform connectivity and throughput comparisons between alternative MAC-Layer technologies (i.e., TDMA vs TCeMA).

Topics

- Network overview
  - How we find neighbor spacecraft
  - … close the link at high data rates
  - … reuse the spectrum multiple times over
  - … integrate time-code and spatial multiplexing
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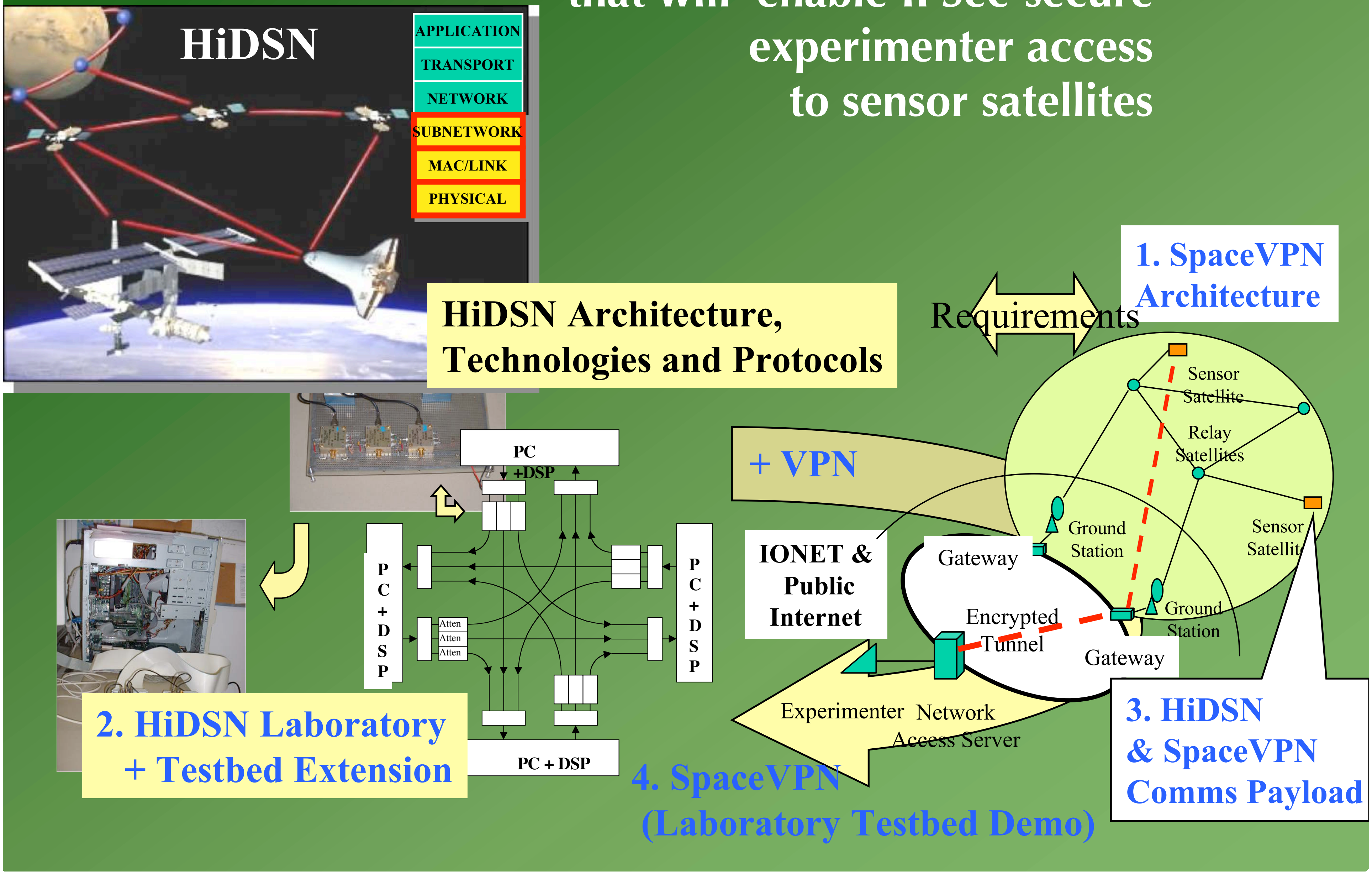
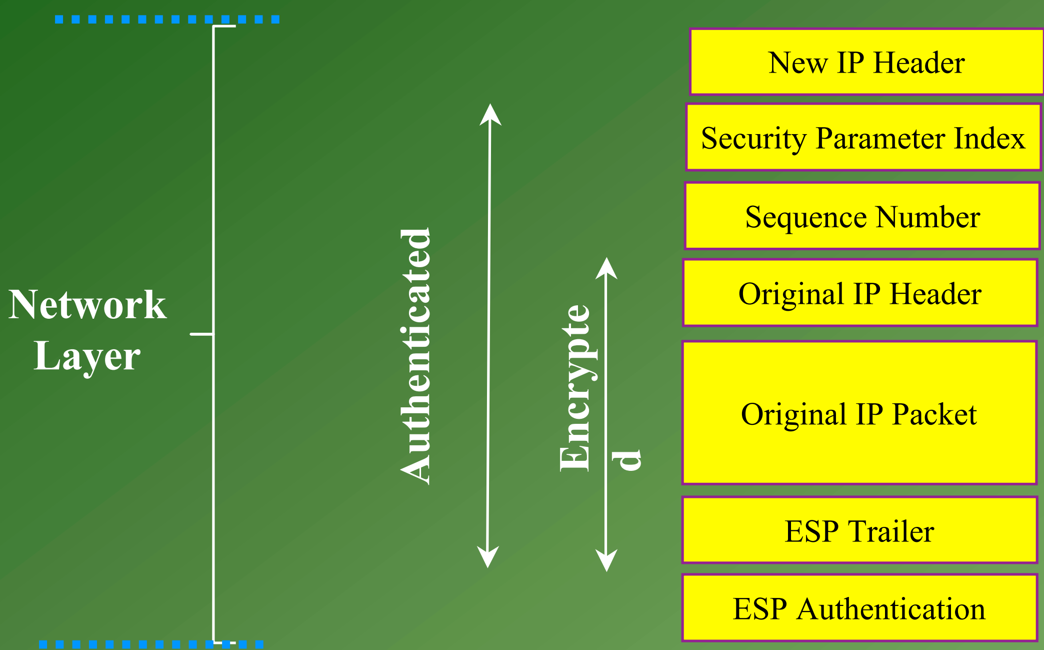
  - IPSec-secure experimenter access to on-board instruments

Next... SpaceVPN will extend the HiDSN by creating baseline architecture and technologies that will enable IPSec-secure experimenter access to sensor satellites

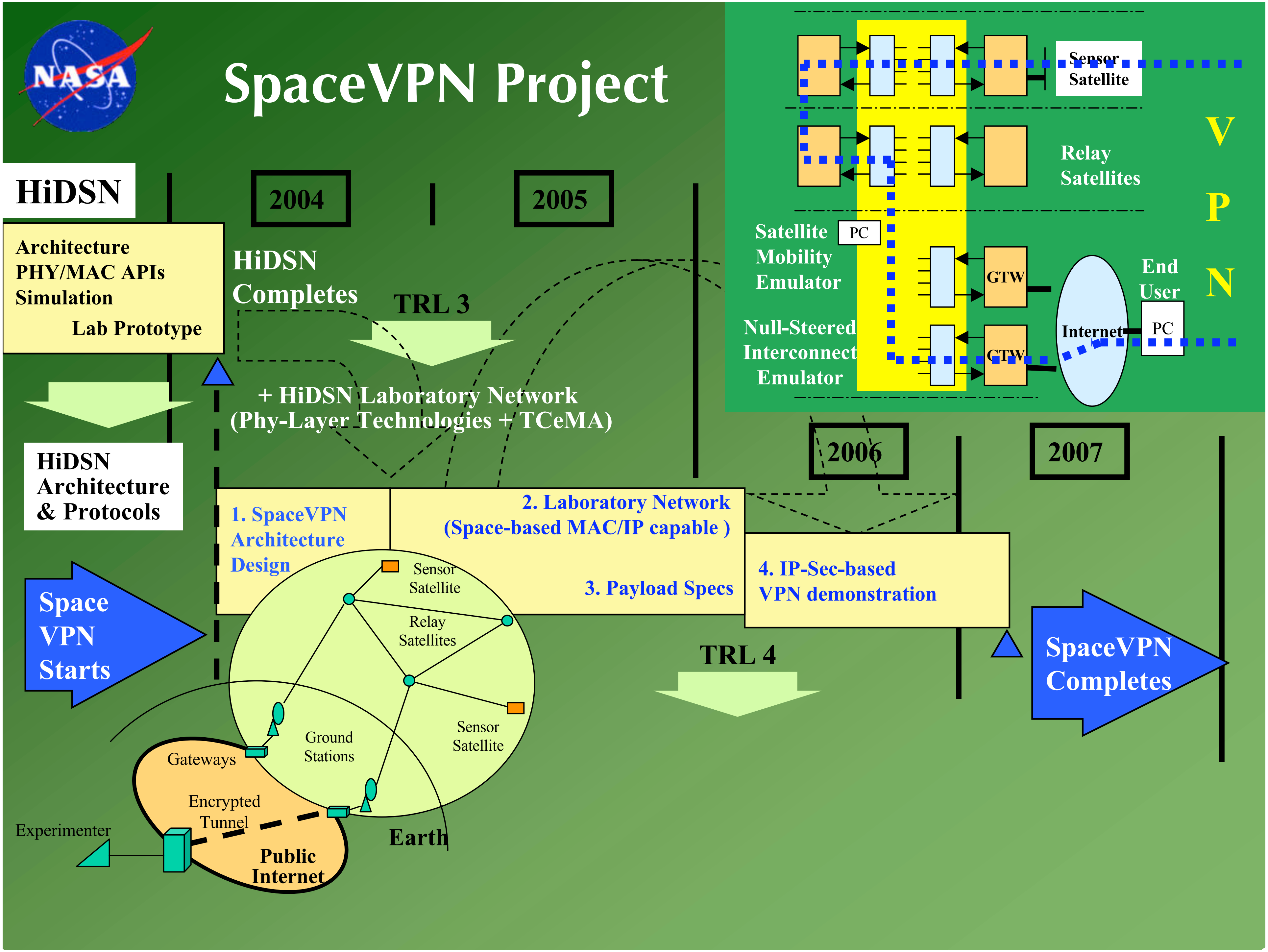


SpaceVPN: Will Add Support for IPSec



Example: IPSec packet with ESP in tunnel mode

Source: W. Timothy Strayer, "Privacy issues in virtual private networks," Computer Communications 27 (2004)



SpaceVPN Project
HiDSN
2004
2005
2006
2007
Architecture
PHY/MAC APIs
Simulation
Lab Prototype
HiDSN Completes
TRL 3
+ HiDSN Laboratory Network
(Phy-Layer Technologies + TCeMA)
HiDSN Architecture & Protocols
Space VPN Starts
1. SpaceVPN Architecture Design
2. Laboratory Network
(Space-based MAC/IP capable)
3. Payload Specs
4. IP-Sec-based VPN demonstration
TRL 4
SpaceVPN Completes
Sensor Satellite
Relay Satellites
Ground Stations
Sensor Satellite
Gateways
Encrypted Tunnel
Public Internet
Experimenter
Earth
Sensor Satellite
Relay Satellites
Satellite Mobility Emulator
PC
Null-Steered Interconnect Emulator
GTW
GTW
Internet
End User
PC
V
P
N

SpaceVPN will build upon HiDSN Development. Relevant HiDSN results include:

[1] M. Bergamo and S. Ramanathan, "High-Throughput Distributed Spacecraft Network (Hi-DSN): System Design," Project Report, NASA Contract No. NAS3-01101, February 14, 2003.

[2] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN): Physical-Layer API Specification," Project Report, NASA Contract No. NAS3-01101, October 23, 2003.

[3] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN): MAC-Layer Design," Project Report, NASA Contract No. NAS3-01101, March 30, 2004.

[4] R. Hain and S. Ramanathan, "High-Throughput Distributed Spacecraft Network (Hi-DSN: Comparing Multiple Access Protocols for the Distributed Spacecraft Network: A Simulation Study using OPNET," Project Report, NASA Contract No. NAS3-01101, December 2002

[5] M. Bergamo, "High-Throughput Distributed Spacecraft Network (Hi-DSN): TCeMA Scheduling: Algorithm for Burst Transmission Time Calculation," Project Report, NASA Contract No. NAS3-01101, September 3, 2003.

[6] M. Bergamo and R. Hain, "High-Throughput Distributed Spacecraft Network (Hi-DSN: A Full Capability Simulation Study Using OPNET," Project Report, NASA Contract No. NAS3-01101, March 26, 2004.

[7] R. R. Hain, S. Ramanathan, M. Bergamo and T. M. Wallet, "Comparison of TCeMA and TDMA for Inter-satellite Communications using OPNET Simulation," OPNET Work 2003, August 25 – 29, 2003.

Questions…

- …